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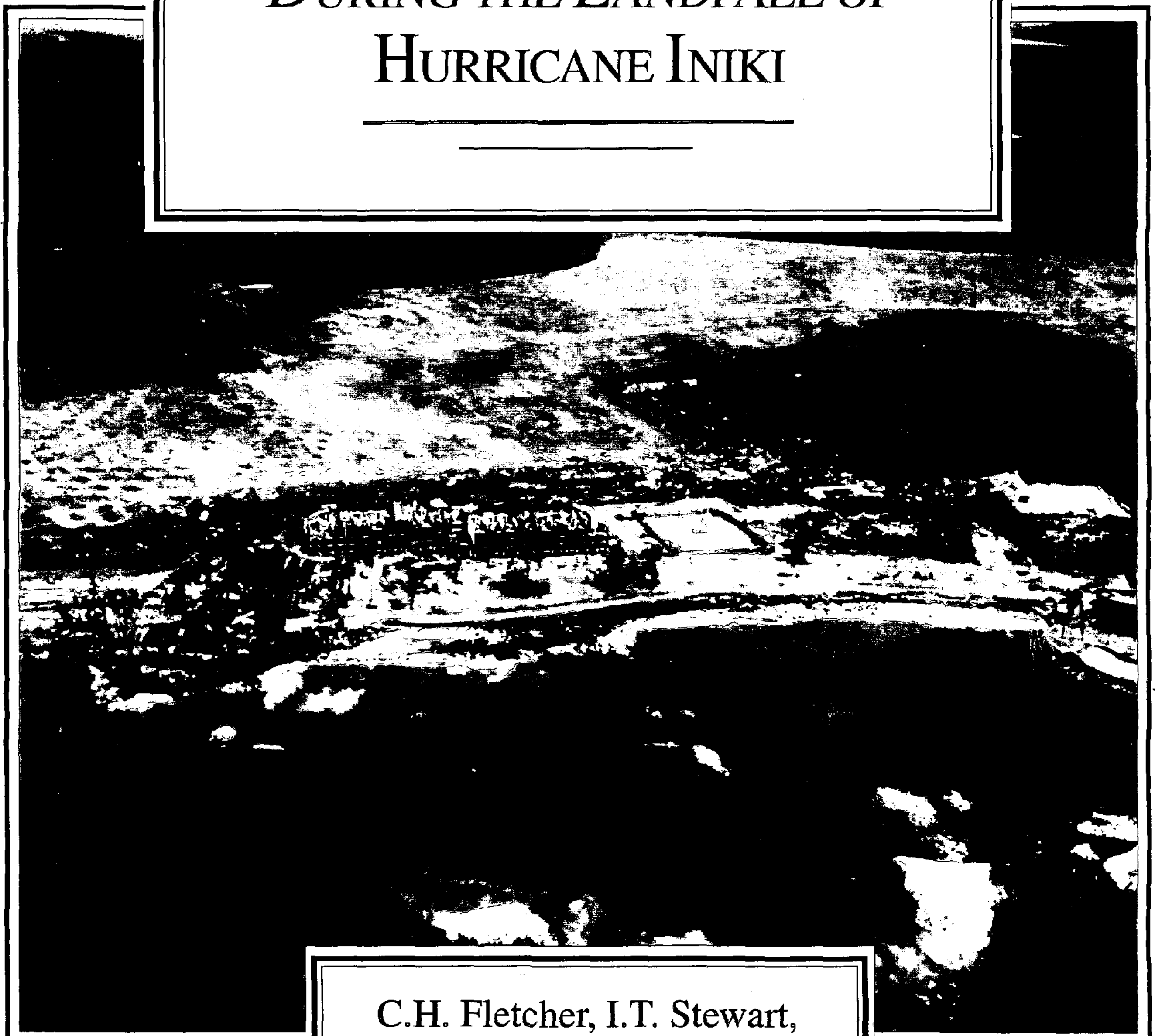
Estimation Analysis and Mapping of Coastal Overwash on Kaua'i During the Landfall of Hurricane Iniki



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COVER: The marine overwash of Hurricane Iniki on the southern coast of Kaua'i left a line of debris behind this condominimum complex near Kukuiula Harbor. The lower floors, and the foundation, were damaged by marine floodwaters. The upper floors and roof were destroyed by wind. Beach erosion exposed soil layers that caused coastal turbidity for several weeks following the storm.

COASTAL OVERWASH ON KAUA'I DURING HURRICANE INIKI

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Coastal Overwash on Kaua'i During Hurricane Iniki

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-EXECUTIVE SUMMARY-

Hurricane Iniki was a minimal Category 4 subtropical cyclone that crossed Kaua'i September 11, 1992. The eye made landfall at Kaumakani at approximately 3:20 pm and departed the north shore by 4:00 pm. The loss of life was miraculously minimized. Economic losses from high winds and marine overwash rank the storm as the fifth costliest insured catastrophe in U.S. history and the worst recorded storm in Hawaiian history.

This is a study of the marine overwash of Kaua'i during Iniki. The goals of the study are to provide a numerically estimated description of the meteorologic and oceanographic environment that contributed to the overwash, to map the overwash line at significant points around the island, and to describe impacts to the offshore environment of the south shore. The research was supported by the Hawai'i Coastal Zone Management Program pursuant to N.O.A.A. Award No. NA36OZ0022-01, the National Coastal Geology Program of the U.S. Geological Survey, and the National Science Foundation.

Analysis of the initial set-up and astronomical tide, the pressure set-up, wind and wave set-up, and wave run-up provides a description of overwash components. These are compared to observed overwash elevations at two areas on the southern Kaua'i coast, near Kukuiula Bay, and on the Poipu-Koloa coast. Our estimations match the field observations.

Location	Initial	S_p	S_{ww}	ΔS_w	R_{uv}	Total	Observed
Kukuiula	1.8ft	1.32 ft	5.3 ft	0.2 ft	9.3 ft	~18 ft	17.2 ft
Koloa-Poipu	1.8 ft	1.21 ft	5.3 ft	0.2 ft	14 ft	~22.5 ft	19.7-27.8 ft

Overwash maps are provided and discussed for five localities: Kekaha, Waimea, Hanapepe, Kukuiula to Keoniloa Bay, and Wailua to Kapaa. A continuous overwash line along the south and east coasts of Kaua'i is archived in the State of Hawai'i Geographic Information System. GIS basemaps for the five regions displayed here depict the FEMA FIRM V-Zone and A-Zone, as well as the 1986 GIS shoreline, and Iniki overwash.

Diver surveys between Kukuiula to Makauena Point determined that no significant structural-debris accumulation is found in the marine environment. Comparisons of coral-distribution data spanning 20 yr indicate a one-third reduction in total coral coverage along the 30 ft depth contour. Along the 70 ft contour, total coverage has not changed, but previously dominant encrusting genera have been replaced by genus *Pocillorpora*.

Figure 1. Overwashed and wind-blown sand on the coast road at Kekaha.

-INTRODUCTION-

Shortly after 3:00 PM (HST) on September 11, 1992, Hurricane Iniki made landfall on the south shore of the island of Kaua'i. The eye passed the Kaua'i coast near Kaumakani (~5 km west of Port Allen) with devastating consequences. Sustained winds of about 130 mph, gusting to 160 mph, and extensive coastal flooding commonly exceeding 10 ft in elevation, destroyed or damaged 14,350 houses. Of these, 1,421 were destroyed, and another 5,152 suffered major damage. Statewide, an additional 607 houses sustained damage or were destroyed. Six deaths are attributed to the storm, and over one thousand injuries reported. A year later, the Property Claims Services Division of the American Insurance Services Group, and the Insurance Information Institute, ranked the $1.6 billion (1990 dollars) in losses from Iniki as the fifth most costly insured catastrophe in U.S. history.

The principal goal of this report is to provide maps of the overwash pattern on Kaua'i in and around the population centers of Kekaha, Waimea, Hanapepe, Kukuiula to Poipu, and Kapaa. We also describe environmental and meteorological factors that influenced overwash impacts in the coastal zone of Kaua'i. Principal attention is given to the south shore of the island, in the right forward quadrant of the storm as it made landfall. It was here that overwash was most intense. Using field investigations, marine surveys, and aerial photograph analysis, the overwash zone was mapped around the island, and digitally recorded in the Office of State Planning Geographic Information System. We also report on weather and marine conditions during the overwash and discuss impacts to the offshore coral community.

Separate reports on various aspects of the Iniki tragedy are emerging from various concerned economic and scientific sectors of our society. Many

Figure 2. An 80 unit condominium complex, lower floors destroyed by overwash, upper floors destroyed by wind. Note the overwash debris line in the background. East of Kukuiula Bay, Kaua'i (see cover).

of these have overlapping coverage, and, we have found, to some degree report conflicting details. To the extent possible here, we utilize the most reliable and reasonable of these in our own descriptions. Our approach is to estimate, through field data and simple numerical calculations, the meteorological and oceanographic processes that both mitigated and exacerbated the marine overwash of Kaua'i during Hurricane Iniki.

At this writing, one year later, Kaua'i still struggles to recover her lifestyle and economy. It our sincere hope that the contributions in this report provide some lessons that may help mitigate future levels of tragedy.

Figure 3. The Bull Shed Restaurant, Kapaa. Overwash reached >2 m.

-STORM HISTORY-

Iniki was first identified as Tropical Depression (TD) 18-E approximately 2690 km southwest of Baja California over the warm waters of the eastern Pacific near 12°N 135°W on September 5, 1992. Meteorologists at the National Weather Service in Silver Spring, Maryland, and at the Central Pacific Hurricane Center in Honolulu, speculate that the storm may have originated in August as a mid-tropospheric tropical wave off the coast of Africa. An area of disturbed weather was tracked by the National Hurricane Center across Central America for several days when it moved into the Pacific on August 28. TD 18-E crossed 140°W and moved into the Central Pacific on the morning of September 6 heading west-northwest at 7 m/sec with maximum sustained winds of 15 m/sec. Initially expected to dissipate, TD 18-E did weaken under unfavorable wind shear, but by mid-day on September 7 the system became imbedded in a deep easterly flow along the southern edge of the seasonal subtropical high-pressure ridge extending from 40°N to 45°N latitude between 130°W and 170°W longitude. By 5 pm that day, TD 18-E was upgraded to Tropical Storm Iniki moving west at 4.5 m/sec with maximum winds of 18 m/sec.

Tuesday, September 8 - Iniki slowly intensified as it moved west with maximum sustained winds of 20 m/sec. Forecast to head west-northwest, Iniki continued west at 7 to 7.5 m/sec throughout the day as winds strengthened to over 30 m/sec with gusts to 38 m/sec by 5 pm. At 11 pm, Tropical Storm Iniki was upgraded to Hurricane Iniki at a position of 13.2°N 152.1°W moving still west with maximum sustained winds of 34 m/sec, gusting to 40 m/sec. With a forward translation speed of 7 m/sec, Iniki's central pressure slipped to 992 mb as the hurricane assumed a new

FIGURE 4. Houses in the Kukuiula Bay area, on the south coast of Kaua'i, were subjected to gusts reaching 64 m/sec and overwash reaching elevations 4.5 to 5.2 m. Houses were swept from their foundations and carried inland as much as 100 m by the inundation. Those buildings that remained in place were battered by boulders and debris carried in the raging sea, and flooded through their lower levels. Simultaneously, the wind ravaged the uppermost floors. Demolished structures along the waterline, such as seawalls, poured concrete lanai's, and paving stone acted as battering rams when carried by the overwash. Several homes sited on bluffs near Koloa landing were damaged by breaking waves reportedly exceeding 8 m in height.

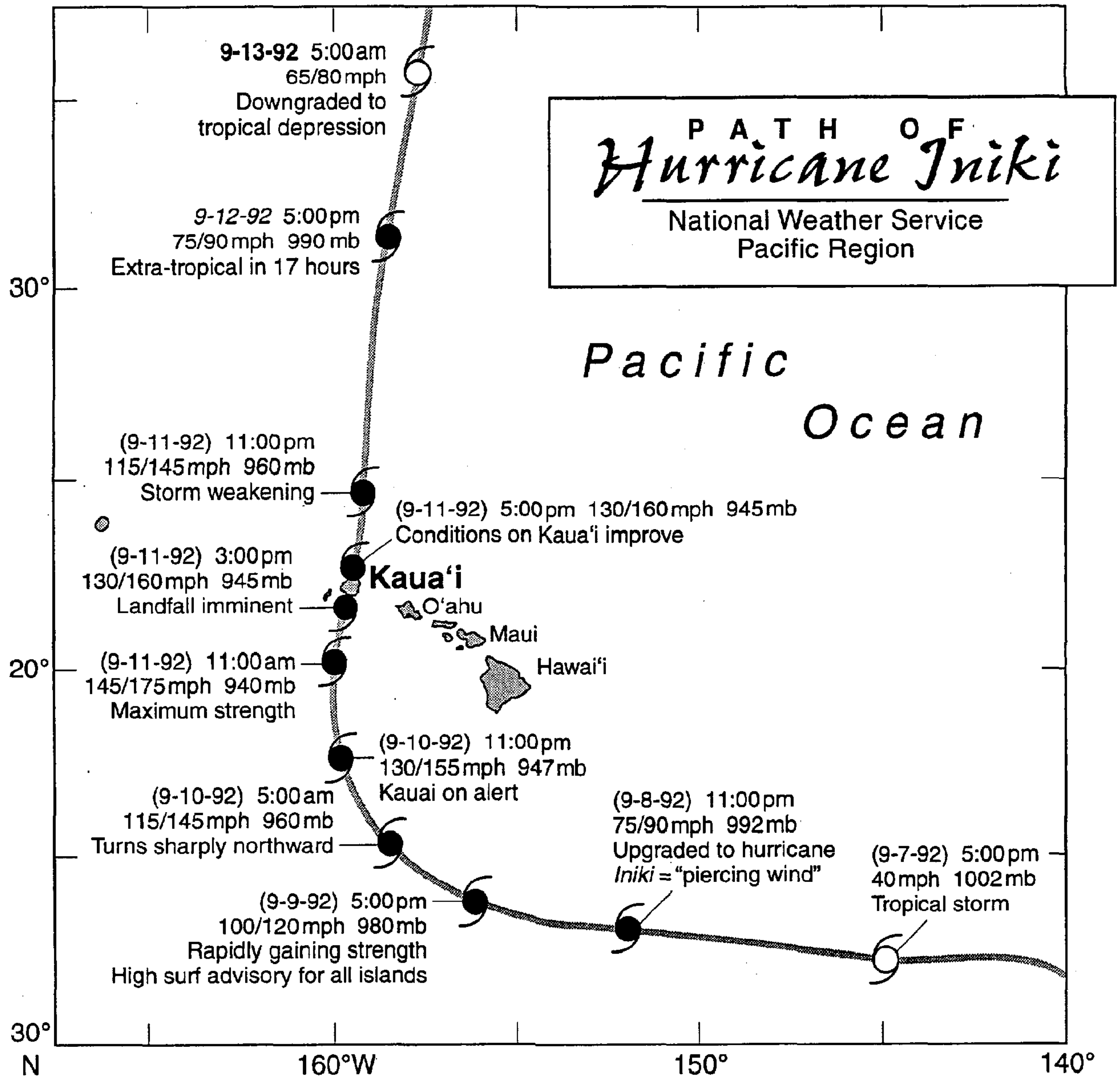


Figure 5. Path of Hurricane Iniki, and significant episodes in the evolution of the storm (National Weather Service).

heading to the west-northwest by 5 am, the next day.

Wednesday, September 9 - At 6 am, high surf advisories for the south-facing shores of the Big Island were issued. Predictions called for waves between 1.2 and 2.5 m high. When the swell eventually arrived, 11 hours later, it measured 2.5 to 3.5 m. By 11 am, sustained winds had strengthened to 40 m/sec and gusts exceeded 49 m/sec. Expected to strengthen still further, the system continued tracking west-northwest and by late afternoon was approximately 484 km south of South Point, Hawai'i. Iniki was now heading west-northwest at 6.3 m/sec with maximum sustained winds of 45 m/sec, and gusts to 54 m/sec.

At 5 pm, a high-surf advisory was issued for the south-facing shores of all Hawaiian islands. By 11 pm on September 9, a USAF reconnaissance plane found a "small intense hurricane with gale winds out 240 km in the north semicircle." At this point Iniki was gusting to 56 m/sec, and central pressure had dropped to 980 mb.

Thursday, September 10 - Iniki increased in intensity (sustained 52 m/sec, gust 65 m/sec, 951 mb) but did not change from its heading of a day earlier. This situation was similar to previous hurricane systems that had ventured near Hawai'i. Had Iniki continued on its path toward the western edge of the Central Pacific subtropical high pressure ridge at 145°W, it would have never approached the State any closer than its earlier position south of the Big Island. However, further west, a large upper low pressure system and cold trough had moved southward along and just east of the dateline. A low pressure area associated with this movement developed near 30°N just east of the trough. This was destined to turn Iniki to a more northerly track. The position of the storm at the time it turned and the path it followed would determine the level of threat to the islands of O'ahu and Kaua'i.

During the morning hours of September 10, Iniki, located 675 km south-southwest of Honolulu, ominously slowed its forward motion to 5 m/sec and maintained its earlier intensity. Throughout the afternoon, however, conditions changed as the storm grew in strength and moved on a new heading to the north-northwest. By 5 pm on September 10, Iniki turned to the northwest. Having continued to grow in intensity with top winds of 56 m/sec, gusting to 69 m/sec, the center was now located near 16°N and 160°W, 645 km south of the city of Lihue on Kaua'i.

A hurricane watch was issued at 5 pm for islands from Kaua'i to French Frigate Shoals. Reconnaissance plane and satellite pictures indicated a strengthening of the storm, and forecasters predicted the storm would follow a northwest track at about 4 m/sec. A National Weather Service news release at 5 pm forecast a slow weakening of the storm as it turned on a more northerly track, eventually passing 320 km west of Kaua'i within 48 hours. Surf was reported subsiding on the Big Island, and building to 2.5 to 3.5 m elsewhere. The south shore of Kaua'i was warned of sustained, rough surf that would damage shoreline property by Friday. By 8:30 pm the alert was elevated. A Hurricane Warning was issued for Kaua'i and Ni'ihau, a Tropical Storm Warning for O'ahu, and a Tropical Storm Watch for Maui Co.

> "Iniki has turned on a more northerly track. Eye forecast to move close to Kaua'i and Ni'ihau. Position 16.8°N and 159.5°W with max. winds 125 mph and gusts to 155 mph. Iniki moving NNW 14 mph."
>
> National Weather Service Release, 8:30 pm HST Thu. Sept. 10, 1992

Within two and a half hours the alert status was elevated again. This time O'ahu was upgraded to a Hurricane Warning.

> "Hurricane Warning issued for O'ahu...Upgraded from Tropical Storm Warning. Hurricane warning continued for Kaua'i and Ni'ihau. Hurricane Watch continued for islands west of Kaua'i to French Frigate Shoals. Position 17.5°N, 160.0°W moving north 15 mph with max winds 125 mph and gusts to 155 mph. Tropical Storm Watch remains in effect for Maui Co."
>
> National Weather Service Release, 11:00 pm HST Thu. Sept. 10, 1992

Friday, September 11 - Throughout the night of Sept. 10, and into the early morning of Friday, Sept. 11 Iniki accelerated and strengthened as it continued to turn to the north. All warnings and watches remained unchanged as Iniki marched north at 6 m/sec with maximum sustained winds of 65 m/sec, and gusts to 78 m/sec. By dawn on Sept. 11, residents of O'ahu and Kaua'i, who had been awakened earlier by several punctuated blasts on the public siren system, were securing their homes and listening to continuous media coverage on the progress and predictions of Hurricane Iniki. "Life-threatening" surf of 9 m or more was predicted for Kaua'i and Ni'ihau by the evening. Building surf and waves of 3 to 6 m were forecast for the south and west-facing shores of O'ahu. Torrential rains and major flooding were expected on Ni'ihau and Kaua'i by nightfall.

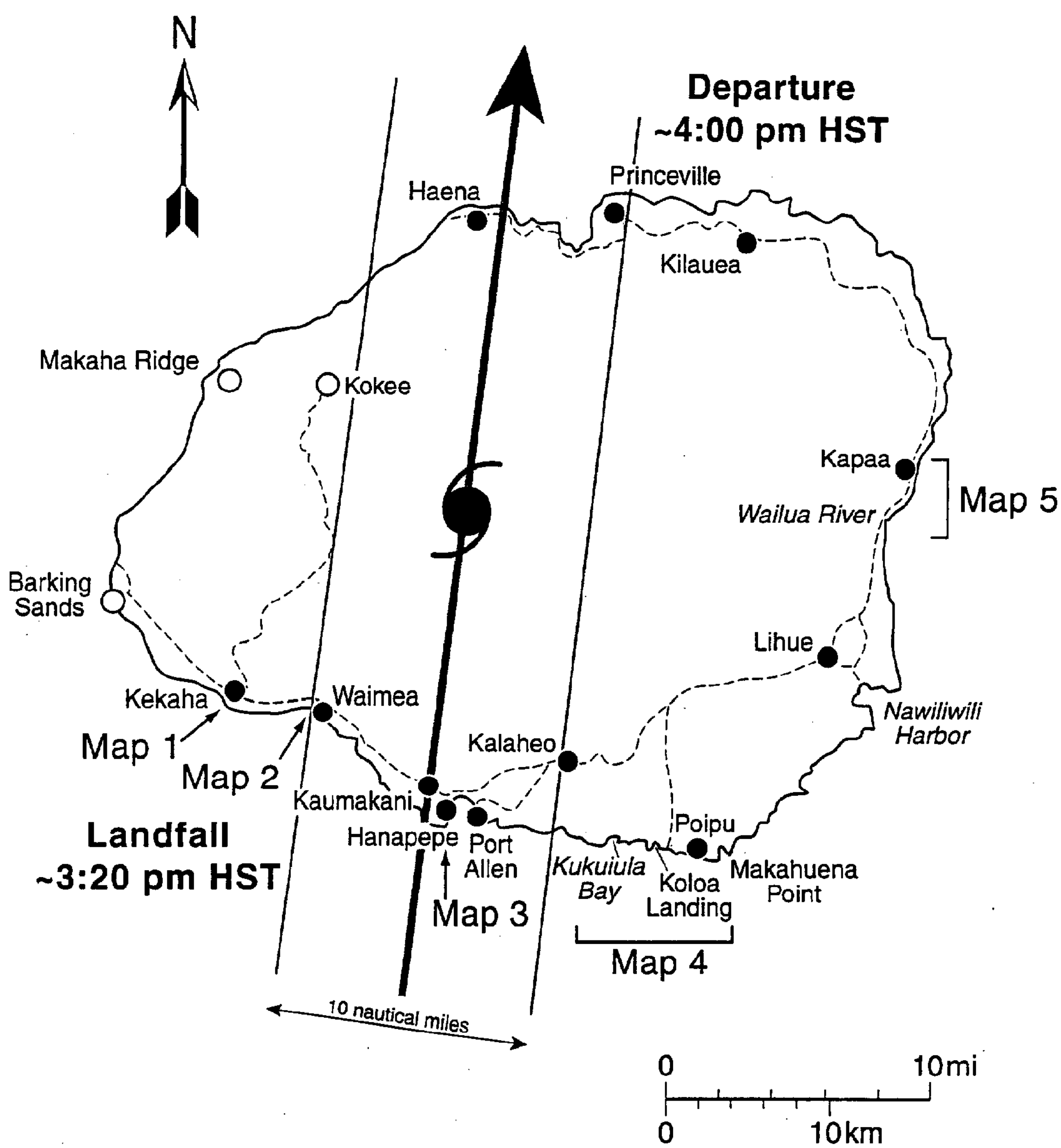


Figure 6. Map of Kaua'i, and path of Hurricane Iniki.

By late morning, 11 am, Iniki had reached maximum recorded strength due west of Maui and 210 km south-southwest of Lihue. Reconnaissance aircraft sent back reports of sustained maximum winds of 65 m/sec gusting to 78 m/sec, and a central pressure of 938 mb, the lowest ever recorded in a Central Pacific Hurricane. The eye diameter was only about 33 km, a small tight center with intense energy. On Kaua'i, the first waves were reported crossing the coastal highway at Kekaha and Poipu. Winds had built to 18 to 22 m/sec between Kekaha and Kalaheo. On O'ahu, the Civil Defense ordered that all persons residing within "300 ft" of all shores evacuate to higher ground. Flash flooding was forecast for O'ahu, Kaua'i, and Ni'ihau.

Iniki moved northward toward Kaua'i throughout the day. A series of slight wobbles in the movement of the eye led to short-term speculation that the storm had turned to the east and was on a path for the Kaua'i Channel, between the Islands of O'ahu and Kaua'i. These reports came through the media at about the same time that power was being lost to much of O'ahu, and the Honolulu waterfront was being overwashed in places to an elevation of nearly 2 m. As power failed, many residents of O'ahu spent the afternoon fearing that Iniki would pass close enough to cause major damage to the entire island. However, by 3 pm Iniki was 60 km southwest of Lihue and moving north, poised to strike the coast of Kaua'i.

As Iniki made landfall west of Port Allen on Kaua'i shortly after 3 pm, the eye was only 18.6 km wide. A small eye diameter normally indicates that strongest winds are located near the eyewall (Trapp, 1993). Unfortunately, no usable wind data is available from near the eye. The NOS tide station at Port Allen did record a low pressure of 960 mb at 3 pm, and 968 mb at 4 pm. Extrapolation of the hourly pressure record suggests a minimum pressure of about 952 mb at Port Allen (NWS, 1993). Twenty kilometers to the east, at Makahuena Pt., an anemometer recorded sustained winds at 36.3 m/sec before it failed. A peak gust of 64 m/sec was later extracted from the digital data recorder at Makahuena. At Lihue, 32 km east of the eye as it passed over the island, sustained winds of 43.5 m/sec (3:52 pm) and a peak gust of 57.8 m/sec (3:02 pm) were recorded.

By 5 pm, having left the island along a path between Haena and Wainiha, Iniki was already 80 km north of Kaua'i, and the Hurricane Warning for O'ahu was downgraded to a Tropical Storm Warning. In confusion, some officials concluded that this new warning heralded the approach of a second storm. All warnings for the State were either cancelled or downgraded by 11 pm as Iniki sped on to the north. High Surf Advisories were maintained the following day for south and west-facing shores of all islands. September 12 dawned with clear skies as citizens of Kaua'i faced the task of recovering from the worst recorded catastrophe in the State's history.

-MARINE CONDITIONS-

Coastal overwash results from the movement of a hurricane across the ocean surface when it encounters land. Flooding of the coast is the product of a number of meteorological and oceanographic factors related to:

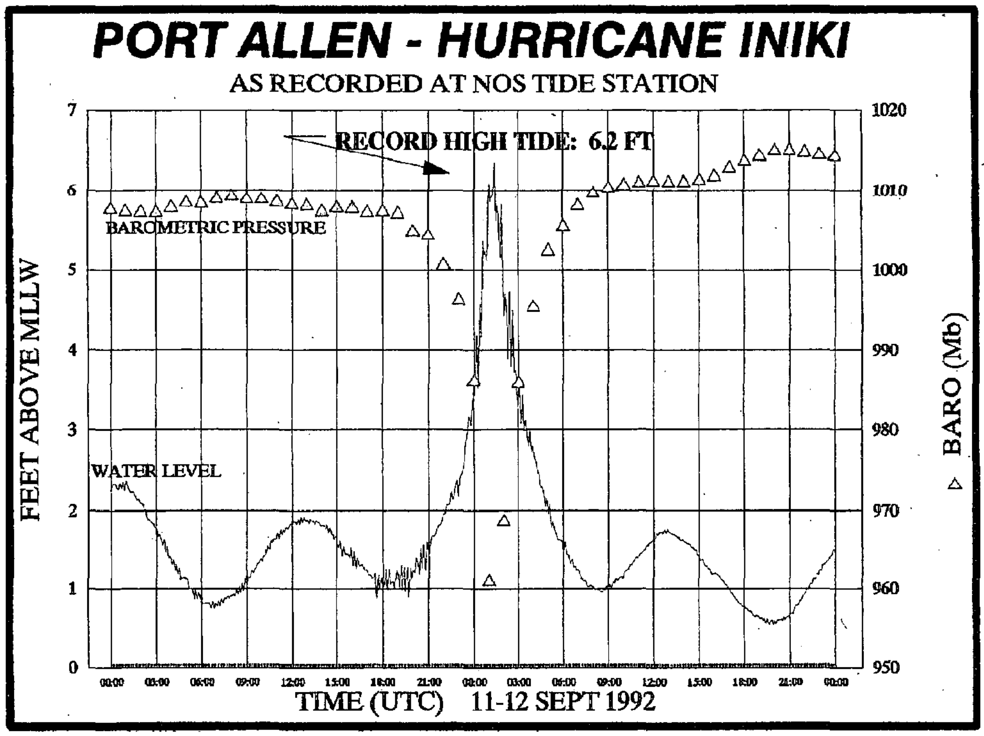
-Initial set-up of the water from either an early arriving long wave, or local sea-level anomalies, plus phasing of the astronomical tide
-Pressure set-up from decreased atmospheric weight on the water column
-Wind set-up from the shear of the winds across the water surface
-Wave set-up effects inside the breaker zone
-Wave run-up controlled by bathymetry, topography and surface roughness
-Shape of the coastline, and bathymetric morphology

Other factors adding to overwash, such as rainfall and the Coriolis effect are usually considered negligible on open ocean coasts lacking run-off collection basins such as estuaries and lagoons, or shoreline features perpendicular to the mass movement of deflected water.

Typically the region in the right front quadrant of a moving storm experiences the greatest wind shear because the speed of the storm adds to the actual wind velocity. When a storm crosses a shoreline, or moves adjacent, the combined effects of storm surge and high waves can cause flooding, called overwash. Overwash can lead to coastal erosion, loss of soil fertility and standing-water quality by salinization, damage to buildings and transportation networks, interruption of power and communication grids, bodily injury and loss of life, and crop destruction. Numerous secondary effects may result from overwash, including landsliding, excessive coastal turbidity with deleterious effects on the coastal ecosystem, and even elevated seismic risk in seismically active regions associated with the dramatic pressure changes. The decrease in the weight of air in a hurricane can be as much as 2-3 million tonnes per km^2 of land over a matter of hours (Bryant, 1991). Overwash on the order of 8-10 m in height can lead to an increase of pressure on the earth's surface of 5-7 million tonnes per km^2. Areas such as the south shore of the Big Island may be under enhanced seismic risk during landfall of a hurricane.

In the following estimation analysis we attempt to unravel the various components that additively comprise the rise in sea-level that led to flooding of the Kaua'i shore in the region between Kukuiula and Poipu. More detailed descriptions are provided in Agrawal (1993) and, based on his analysis, Bretschneider et al. (1993). We also refer the reader to the excellent modeling of Sea Engineering and Bretschneider (1986). Their worst case scenario predicts the overwash experienced on this coast during Iniki. A report currently being generated by the U.S. Army Corps of Engineers also tackles this problem (Yamamoto and Sullivan, 1993). These references provide the reader with more detailed descriptions of the numerical approach.

Our assumptions simplify our findings. We use a maximum deep water wave height, maximum wind speed, and we reduce the complicated coastal zone experiencing overwash to a uniform, rough slope extending approximately from the wave break point to the upland 6 m contour. Our analysis is only applied in two locations, east of Kukuiula Harbor, and between Koloa Landing and Poipu Beach Park. It is not our purpose to produce a new numerical model of overwash, rather it is our goal to understand the relative components of overwash. In so much as our final estimations of overwash are close to observed values, our analysis has achieved its goal.



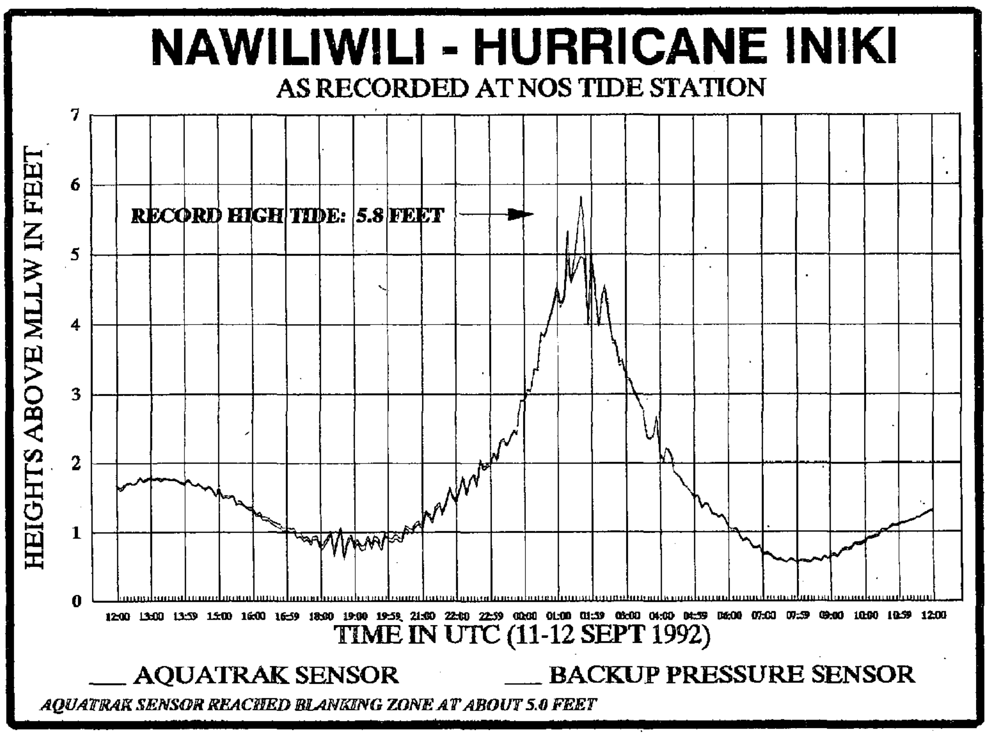


Figure 7. Tide gauge records from Port Allen and Nawiliwili during Iniki.

INITIAL SET-UP

If a decrease in atmospheric pressure should suddenly be applied to the ocean surface, a wave will be generated with a celerity that is depth dependent. Over the open sea the velocity of propagation of such long waves is 180 to 270 m/sec and thus the storm cannot keep pace. This long wave arrives at the coast as a "forerunner", and may raise the still-water level as much as 0.5 m or more. Sea Engineering and Bretschneider (1986) argue that the forerunner should not be treated as an explicit term because it is accounted for in the wave set-up and pressure set-up. In Agrawal (1993) it is treated with the astronomical tide. Values for initial set-up on the Texas coast have been found to be 0.6-0.75 m (Marinos and Woodard, 1968). Initial set-up values on the Atlantic coast are typically lower than either Gulf coast or Pacific values.

Because the forerunner is poorly understood, and cannot be accurately predicted, we will express it imbedded within the astronomical tide component of the sea-level. Based on the available tidal hydrograph data (Fig. 4), Bretschneider et al. (1993) estimate a value of 0.55 m above mllw (local Hawaiian datum) for the combined tide and forerunner at Port Allen at the landfall of Hurricane Iniki. In the hurricane vulnerability study of Poipu, Kaua'i, Sea Engineering and Bretschneider (1986) use a value of 0.52 m (1.7 ft) for their scenario hurricanes because of the frequency of occurrence of this tide level. Landfall of the eye of Hurricane Iniki unfortunately coincided with the peak diurnal astronomical tide for the day, thus the resulting overwash was enhanced by the phased tide and surge. As Iniki crossed the coast of Kaua'i, then, the initial water-level was at or near a maximum, and damage was exacerbated.

PRESSURE SET-UP

The water-level increase, or set-up (S_p), due to a pressure variation (Δp) on the surface of the ocean is a function of the pressure drop from the periphery to a point within the hurricane ($\Delta p/\rho_{sw}g$), where ρ_{sw} is the density of seawater (1025 kg/m^3). Myers (1954) developed an empirical relation for the surface pressure distribution based on an analysis of historical data.

$$p_a - p_r = [(p_a - p_c)\,100](1 - e^{-RMW/r}) \qquad (1)$$

Where p_a is the ambient pressure (assumed to be 1013.3 mb), p_r is the pressure at any distance r from the center, and p_c is the central pressure of the storm (945 mb). RMW is the radius of maximum sustained wind, usually somewhere in the eyewall. Thus, the set-up becomes,

$$S_p = [(p_a - p_r)(100)/(\rho_{sw} g)] \qquad (2)$$

$$= [(p_a - p_c)(100)/(\rho_{sw} g)]\,(1 - e^{-RMW/r}) \qquad (3)$$

Using (2), the set-up under the center of Iniki, where p_r= 945 mb, becomes 0.68 m (2.2 ft). However, to calculate the pressure set-up outside the center of the storm requires an estimate of the distance of maximum sustained winds, RMW, from the center.

Estimation of RMW and $V_{\theta max}$

The clear eye radius is approximately 9.3 km (reported diameter, 10 nautical miles at sea prior to landfall; Trapp, 1993). Maximum winds, $V_{\theta max}$, will be located an unknown distance beyond the eye, within the wall at the right frontal quadrant of the storm.

An approximation of $V_{\theta max}$ and its location, RMW, begins with a theoretical consideration of the cyclostrophic structure of a symmetrical vortex. The ratio of the square of maximum velocity to the radius of maximum winds ($V_{\theta max}^2$/RMW) is estimated by the inverse of atmospheric density (1/1.1 kg/m^3) and the pressure gradient across some representative distance ($\Delta p/\Delta r$). Dropsonde data near Kaumakani records a central pressure of 945 mb, while 5 km away at Port Allen, the extrapolated pressure record suggests a minimum of 952 mb (NWS, 1993). If we choose a distance of 12 km for the radius of maximum winds, an estimate of the sustained wind around the vortex center is given by

$$(V_{\theta max}{}^{2})/(RMW) = (1/\rho_{atm})\ (\Delta p/\Delta r) \quad (4)$$

$$V_{\theta max} = \left[\left((1/1.1)\ \frac{(952\text{-}945)\ (100)}{5000}\right)\ 12000\right]^{0.5} \quad (5)$$

$$= 40.98 \text{ m/sec}$$

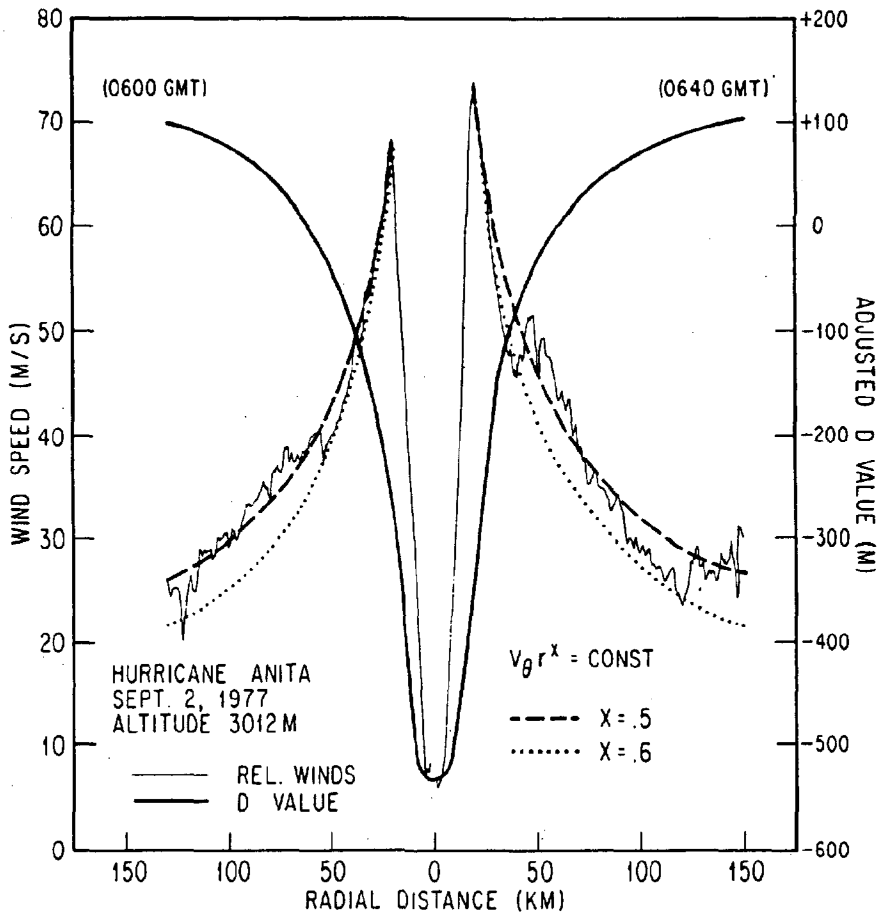


Figure 8. Radial profiles of wind speed (m/sec) and pressure in Hurricane Anita. Note increased velocity to right of eye. Also shown are plots of the Modified Rankine Vortex model, $V_\theta\, r^{(x)}$ for x=0.5 and 0.6 (Anthes, 1982).

This is the stationary velocity. Winds in the right frontal quadrant would have an additional translation speed (Fig. 8). There is some dispute about the actual speed of Iniki as in crossed the south coast of Kaua'i. According to the Iniki Disaster Survey Report (NWS, 1992) the storm had a forward speed of "30 mph" (about 13.4 m/sec). However, in its 3 pm HST news release, prior to landfall, the National Weather Service citing reconnaissance aircraft data reported that "Hurricane Iniki was speeding up(,) moving north at 21 mph" (about 9.4 m/sec). Thus, the effective maximum sustained velocity, $V_{\theta max}$, was in the range of 50.4 m/sec to 54.38 m/sec (52.4±2 m/sec, for an average translation speed of 11.4 m/sec).

NOAA Hurricane Research Division Surface Wind Analysis
Hurricane Iniki 12 Sept, 1992 0006 UTC
based on data between 1100UTC 11 Sept.-0600UTC 12 Sept.
empirical adjustment of Air Force recon winds from 10,000 ft.

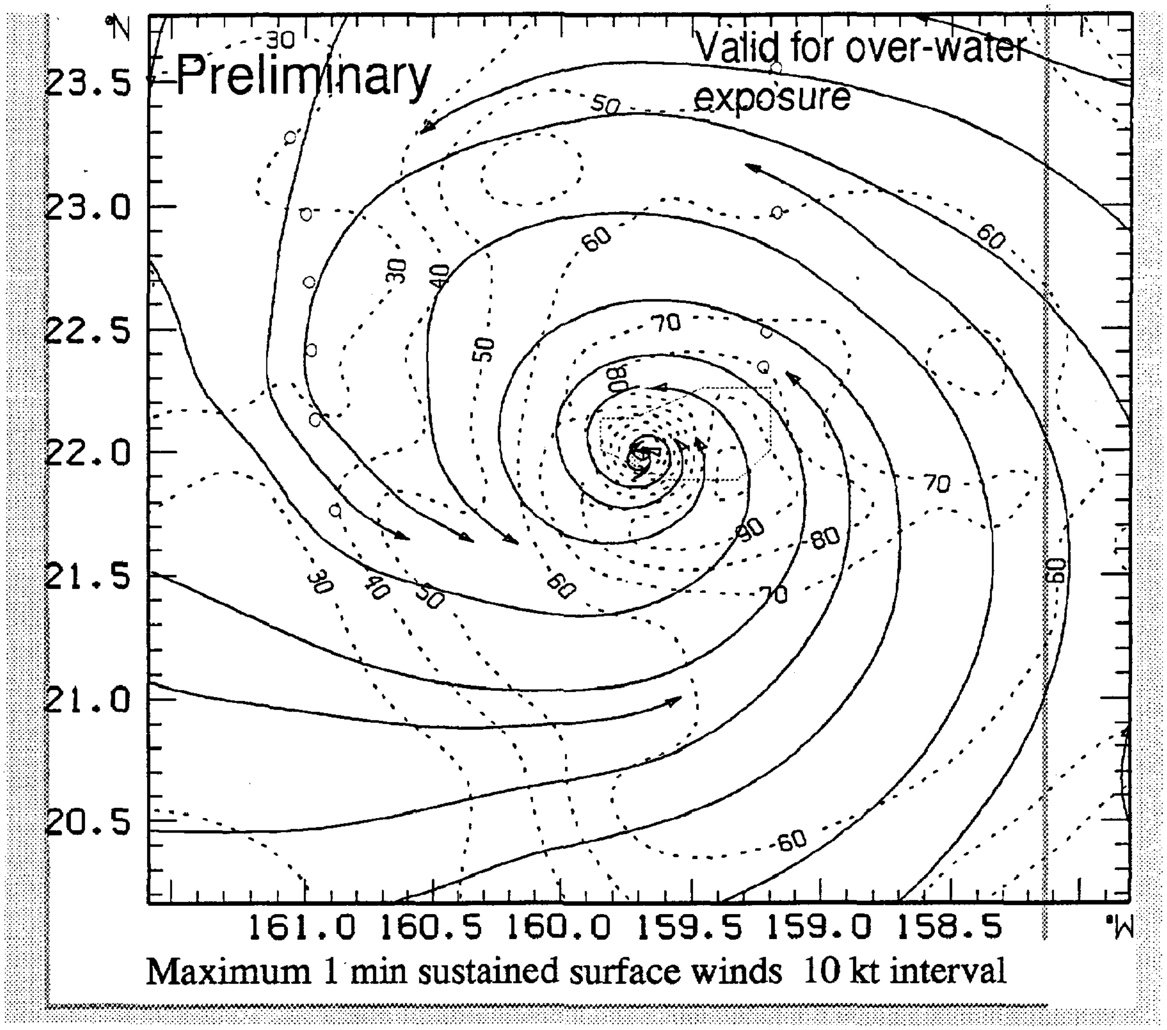


Figure 9. NOAA Hurricane Research Div. surface winds at landfall using empirically adjusted reconnaissance aircraft data (Powell, pers. comm.).

An independent estimation of maximum winds can be performed by several means. Reconnaissance aircraft reported observations of maximum sustained flight-level winds of 65.5 m/sec (127 knots, 146 mph) south of Kaua'i. Powell (1987), in an analysis of the wind structure of Hurricane Alicia (1983) at landfall, suggests a conversion ratio of 0.78 for estimating surface winds from reconnaissance flight-level data. This suggests a value of 51.1 m/sec (99 knots, 114 mph) for maximum sustained winds at or near landfall. Figure 9 shows the preliminary surface wind analysis using empirically adjusted reconnaissance aircraft data (Powell, pers. comm.). This is a close match to the estimate of $V_{\theta max}$ given above.

An alternate method utilizes the Atlantic Empirical Equation, which relates the difference of ambient and observed central pressure to the velocity of maximum wind ($V_{\theta max}=14\ [1013.3\ \text{mb} - 945\ \text{mb}]^{0.5}$) based on historical observations in the North Atlantic basin. This provides a value of 59.6 m/sec (115.7 knots, 133 mph).

Our estimation of 52.4 ±2 m/sec for $V_{\theta max}$ is based upon a number of stated assumptions, each of which may legitimately be challenged. Nonetheless, the value is a reasonable one, and each of the assumptions, by implication, are therefore within the range of possibility. In addition, our purpose in estimating $V_{\theta max}$ is towards the goal of increasing our understanding of the factors influencing marine overwash, and not motivated by pure meteorological curiosity alone.

A number of variables in this evaluation can be modified to allow for a range of $V_{\theta max}$ estimations. The extrapolation of the pressure trace at Port Allen to a value of 952 mb should not be accepted without qualification. It is not a directly measured value, nor is it theoretically derived. In fact, the assumptions upon which it is based were not reported. It is, rather, a "best guess" of what a continuous record might have provided. In addition, equation (3) extrapolates the pressure slope between the center and Port Allen as representative of the entire pressure field on the right side. Is this appropriate? Unfortunately, no other data to constrain the pressure field is available within the RMW. Likewise, the choice of 12 km for the radius of maximum winds is a "best guess", arrived at iteratively, and should not be accepted uncritically. The Atlantic Empirical Equation suggests a $V_{\theta max}$ of 59.6 m/sec. Hindcasting with this value using (3) suggests that the radius of maximum winds is greater, on the order of 15 km for a translation speed of

13.4 m/sec. This is also an acceptable result. So the derivation provided here is not a unique solution. Lastly, as we have stated, the speed of the storm is under question. The NWS (1993) estimates that Iniki crossed Kaua'i between 3:20 and 4:00 pm on Sept. 11, 1992. Covering a distance of 22.2 miles in 40 minutes equates to about 30 mph, giving some credence to the higher number. Nonetheless, we choose to take an average of the two reported values.

An additional test for our assumptions is provided by the data available from Makahuena Point. A maximum gust value of 124 knots was extracted from the digital recorder there. Powell's (1987) analysis of the landfall of Hurricane Alicia provides a useful gust factor of 1.64, suggesting that maximum sustained winds at Makahuena Pt. were about 75 knots (39 m/sec; 87 mph). By calibrating the Modified Rankine Vortex Model (Anthes, 1982) with $V_{\theta max}$, we estimate the maximum sustained winds.

$$V_\theta \, r^{(.5-.6)} = \text{Iniki Constant} = (40.98)\,(12{,}000)^{0.55} \tag{6}$$

$$= 7179.95 \text{ m}^2/\text{sec}$$

$$V_\theta = 7179.95 / r^{(.55)} \tag{7}$$

Makahuena Pt. is a distance (r) of about 20 km from the center. Equation (7) predicts a V_θ of 30.9 m/sec at this location, which becomes 42.3±2 m/sec for a translation speed of 11.4±2 m/sec. Thus, estimates of V_θ at Makahuena Pt. using Powell's gust factor (39 m/sec) and the calibrated vortex model (42.3±2 m/sec) correlate to within 8%, a reasonable fit.

Let us return to a consideration of the hydrostatic pressure set-up (S_p) at points away from the center of Iniki. Using a value of 12,000 m for RMW, with Myers' (1954) pressure distribution relation, we can estimate the pressure set-up at two representative locations where extensive overwash occurred in the region from Kukuiula Harbor to Poipu.

Location	Observed Overwash	r (km)
(1) Kukuiula	~5.2 m (17.2 ft)	16.5
(2) Koloa-Poipu	~ 6-8.5 m (19.7-27.8 ft)	19

$$S_p = [(p_a-p_c)(100)/(\rho_{sw}g)]\,(1-e^{-RMW/r}) \qquad (3)$$
$$S_1 = [0.68]\,(0.52) = 0.35 \text{ m } (1.2 \text{ ft})$$
$$S_3 = [0.68]\,(0.47) = 0.32 \text{ m } (1.1 \text{ ft})$$

This is a time-dependent result however, and it is incomplete until we include a factor for the depth- and time-relative resonance of the hydrostatic set-up by a long-wave generated with the moving storm. These waves reach greatest amplitude when the speed of the storm equals the speed of a shallow water wave [$(gd)^{0.5}$], and when the storm has travelled at the required speed for sufficient time for the wave to completely develop. A factor for the influence of this wave is used to correct the pressure set-up calculated by (3). The critical water depths for hurricane speeds of 10, 20, and 30 knots are 3, 11, and 26 m respectively (Sorensen, 1978). Ewing, et al. (1954) report on a squall moving over the appropriate depth of southern Lake Michigan for 0.5 hr. The hydrostatic set-up (~0.03 m) was amplified by water column resonance and a 1-2 m surge was observed in the path of the squall-generated wave at Michigan City, Indiana.

Based on a laboratory study, Abraham (1964) suggests the long-wave surge can approach twice the value given by (3) if a storm moves over water of between 0.75-1.25 times the critical depth for a period of 1 hr or more, and triple that value for a depth range of 0.9-1.1 times the critical depth for the same period. Iniki moved at speeds between 8.9-17.6 m/sec (15-30 mph) in the period prior to landfall. The critical resonance depth can be calculated from [$d_{cr} = V^2/g$]. Thus 8.1 m $< d_{cr} >$ 31.6 m, and 0.75 d_{crmin} = 6 m, while 1.25 d_{crmax} = 39.5 m. According to Abraham (1964) if the hurricane remains in the depth range 6-39.5 m for an hour then resonance amplification becomes a factor of 2. The bathymetry of the southern Kaua'i coast is steep, and these two depths are an average of 2-2.5 km apart. At an average translation speed of 11.4 m/sec, Iniki would only have remained in this depth interval for 3-4 minutes. Since the resonance factor of 2 requires Iniki to have travelled this depth range for an hour, the resonance factor must be significantly less. But because Iniki was moving, the value must be greater than 1. We will use a value of 1.1 for the resonance factor.

Agrawal (1993) defines a resonance factor, R, that is dependent upon wave celerity and storm translation speed, $[(gd)^{0.5}]^2/([(gd)^{0.5}]^2 - V_f^2)$. He chooses a value of R=1.2, but his criteria are not made clear.

Our values of resonance enhanced, pressure set-up are:

Location	**Hydrostatic**	**Combined (S_p)**
(1) Kukuiula	1.2 (1.1)	1.32 ft
(2) Poipu	1.1 (1.1)	1.21 ft

Wave Set-up

Waves generated by Iniki winds resulted in mass transport into the shorezone that elevated the water level, called wave set-up. In small-amplitude wave theory, water-particle motion in the water column is described with closed orbits, and therefore no net transport of water mass occurs as waves advance to the coast. In reality, measurements of water level inshore of the point where waves break reveals that sea levels increase with larger waves. Thus, some mass transfer of water into the coastal zone must occur as a function of wave characteristics. In real waves, there is a small forward mass transport as water particles advance slightly with each orbit. The velocity of transport increases as wave steepness and wave celerity (speed) increase, and as the relative water depth decreases. As mass accumulates in the breaker zone, currents are generated by the return flow which may move quasi-uniformly along the bottom, or as rip currents spaced periodically along the coast, and as longshore currents moving down a pressure gradient towards areas of lower set-up or offshore flow.

Laboratory and theoretical studies (USACE, 1984) suggest that wave set-up (S_{ww}) can be estimated by

$$S_{ww} = 0.19 \left[1 - 2.82 (H_b/gT^2)^{0.5}\right] H_b \qquad (8)$$

Where H_b is the breaker height in the surf zone, T is wave period. Typically wave set-up will amount to about 15% of the breaker height. In this analysis we neglect the influence of wave-set-down. Breaking wave heights of about 9 m were reported in the region of the Poipu coast at the height of the hurricane. Calculations using solitary wave theory in Bretschneider et al. (1993) suggest that wave heights prior to breaking at Kewalo Basin, O'ahu were in the range 7-8.9 m with periods of 14 sec. Offshore Buoy 51002, located about 280 miles south-southest of Honolulu, recorded a significant wave height of 6 m, with a most probable maximum deep-water height of nearly 11 m (NOS Buoy Data). However, Buoy 51002 is located somewhat off the path of Iniki and we can conservatively estimate deep-water wave heights (H_d) of about 12.2 m (40 ft) for positions along the hurricane track. Agrawal (1993) on the same basis assumes that H_d=45 ft. Equation (9) derives the relationship between breaker height and deep-water height,

$$H_b = H_d/3.3(H_d/L_d)^{0.33} \qquad (9)$$

A deep-water wave length (L_d) can be calculated using ($L_d=[g/2\pi]T^2$). Assuming a wave period of 14 sec, L_d= 306 m (1004 ft). Equation (9) predicts a breaking wave height of 10.7 m (35 ft). Thus, (8) provides an estimate of the wave set-up, S_{ww}, of about 1.6 m (5.3 ft). Pressure set-up and wave set-up are additive:

Location	Initial	S_p	S_{ww}
(1) Kukuiula	1.8 ft	1.32 ft	5.3 ft.
(2) Koloa-Poipu	1.8 ft	1.21 ft	5.3 ft.

WIND AND BOTTOM STRESS SET-UP

A stress (τ_s) is generated as the wind blows across the water surface that is a function of air density (ρ_a), wind velocity (U m/sec), and drag (C_d),

$$\tau_s = C_d \rho_a U^2 \tag{10}$$

Values of C_d typically vary from $1.5x10^{-3}$ for light winds to $2.4x10^{-3}$ for strong winds. Equation (10) is often written relative to water density (ρ),

$$\tau_s = k \rho U^2 \tag{11}$$

where $k = (1.19x10^{-3})C_d$. It has been shown (Van Dorn, 1953) that,

$$k = 1.21x10^{-6} + 2.25x10^{-6} (1-[7.2/U])^2$$

Using our estimation of 52.4±2 m/sec for $V_{\theta max}$, k becomes $3x10^{-6}$. The surface wind stress leads to development of bottom currents that generate a bottom stress (τ_b). Saville (1952) found that $\tau_s+\tau_b=(3.3x10^{-6})\rho U^2$. Assuming that $k = 3.0x10^{-6}$, he suggested that $\tau_s/\tau_b = 0.1$.This can be used to determine a combined surface and bottom stress coefficient K, where ($\tau_s+\tau_b=K\rho U^2$). Thus, K becomes $3.3x10^{-6}$. Across a segment of seafloor normal to the coast of length ΔX, the depth changes from d to $d+\Delta S_w$, where S_w is the set-up due to wind and bottom stresses acting over the length ΔX. Because the water surface slope ($\Delta S_w/\Delta X$) is negligible,

$$\tau_s \Delta X + \tau_b \Delta X + 0.5 g \rho d^2 - 0.5 g \rho (d+\Delta S_w)^2 = 0$$

$$\Delta S_w = d\left[\left([(2KU^2\Delta X)/gd^2]+1\right)^{0.5} - 1\right] \tag{12}$$

Equation (12) is applied sequentially along the bottom profile offshore of the area of interest. Flat sections of bottom of constant depth, d, and length ΔX are used to calculate ΔS_w. The cumulative sum of preceeding set-up values are added to (d) along the profile in the shoreward direction. The highest ΔS_w then becomes the wind and bottom stress component.

Agrawal (1993) provides data on the bathymetry offshore of the Koloa-Poipu region:

Koloa-Poipu Region		
d (m)	ΔX (m)	ΔS_w
5.5	361	0.06 m
18.3	626	0.03 m
91.4	2022	0.02 m
183	2359	0.01 m
		ΔS_{wmax} 0.06 m (0.2 ft)

In this way the combined wind stress and bottom stress set-up under $V_{\theta max}$= 52.4 m/sec becomes about 0.2 ft for the Poipu coast. We will assume the same value for the Kukuiula coast.

Location	**Initial**	S_p	S_{ww}	ΔS_w
(1) Kukuiula	1.8ft	1.32 ft	5.3 ft	0.2 ft
(2) Koloa-Poipu	1.8 ft	1.21 ft	5.3 ft	0.2 ft

WAVE RUN-UP

The extent of wave run-up on a slope is a function of permeability or roughness, bathymetric and onshore slope, coastline configuration, breaking wave height and wave period. In this estimation analysis, we neglect coastline configuration by assuming the bathymetry consists of straight and parallel contours, a common assumption. Although it is not possible to theoretically predict run-up because of the large number of variables, it is possible to estimate run-up from a few simple parameters following the guidelines of some laboratory studies (USACE, 1984).

The following conditions apply: H_d= 12.2 m, T=14 sec, and the slope ($\tan\theta$) from the break point to the 6 m onshore contour at Kukuiula is approximately 0.02, and at Koloa-Poipu approximately 0.03. This approach also neglects the influence of the water column between the break point and the shoreline, and treats the run-up as a simple function of slope and permeability between the break point and the upland. Equation (13) is a modified form of Hunt's (1959) empirical formula relating onshore slope, breaker height and wave period to significant vertical wave run-up [$R_{uv}=T(gH_b)^{0.5}\tan\theta$]. Horizontal excursion can be calculated with $R_{uh}=Tr(gH_b)^{0.5}$, where r is a roughness factor.

We have estimated a breaker height (H_b) of 11 m. Agrawal (1993) calculates a probability parameter (1.5), using wave-energy analysis applied to a modified Hunt formula. This factor converts from significant wave run-up to maximum run-up, with a 2% exceedance, under given hydraulic conditions. Agrawal (1993) and Sea Engineering and Bretschneider (1986) assume a friction value of r=0.85 to estimate the effects of slope permeability and roughness which is a value used to describe grassy slopes. However, the shoreline at both areas of interest is composed of basalt boulders, rocky outcrops, seawalls, and various structures. Accordingly we will use r=0.65.

$$R_{uv}= (1.5)(0.65)\, T[H_b\, g]^{0.5} \tan\theta \qquad (13)$$

Thus, for Kukuiula R_u=2.8 m (9.3 ft), and for the steeper, Koloa-Poipu coast R_u=4.25 m (14 ft).

Discussion

Location	Initial	S_p	S_{ww}	ΔS_w	R_{uv}	Total	Observed
Kukuiula	1.8ft	1.32 ft	5.3 ft	0.2 ft	9.3 ft	~18 ft	17.2 ft
Koloa-Poipu	1.8 ft	1.21 ft	5.3 ft	0.2 ft	14 ft	~22.5 ft	19.7-27.8 ft

Our estimations provide a picture of the relative contribution of the various components comprising the overwash of the south shore of Kaua'i. Clearly, from the point of view of damage in the coastal zone, the most important aspects of the overwash are wave induced set-up and wave run-up. Natural factors that mitigate the wave hazard are a gentle offshore slope, natural roughness of the coastal zone, and the presence of offshore topographic barriers such as a barrier reef and submerged headlands and rocky outcrops. The wave hazard is exacerbated by a steep offshore slope, a featureless bathymetry, initial water set-up, and the pressure and wind stress set-up. Features that mitigate the wave environment under incident hurricane-force winds should be considered in coastal zone management decisions.

The shape of the coastline is an important factor. Any sector of the shoreline that is V-shaped, including submarine topographic channels, will lead to lateral compression of the storm-surge wave, increasing the wave height. The size of such a coastal basin can also lead to resonance if it has a shape that matches the period of any entering wave.

The V-shaped shoreline at Koloa Landing is probably responsible for the highest level of overwash resulting from Hurricane Iniki. Located immediately to the east of Nahumaalo Point, overwash into this narrow embayment, and up the boat ramp and the adjacent Waikomo Stream Valley reached an elevation of over 22 ft. Immediately east of the boat ramp an overwash debris line behind a house measured over 26 ft above mean sea level. Offshore of Koloa Landing, to the immediate west and east, are two submerged rocky platforms, and between them a low-lying coralline-algal surface with a relative relief of about 15 ft. This submerged valley, leading directly to the Koloa Landing area must have channeled and heightened the storm surge and allowed deeper penetration shoreward of the relevant wave characteristics.

It is clear that careful evaluation of offshore morphology and slope should be a consideration in coastal management decisions with regard to development planning and zoning on shorelines with high hazard ratings.

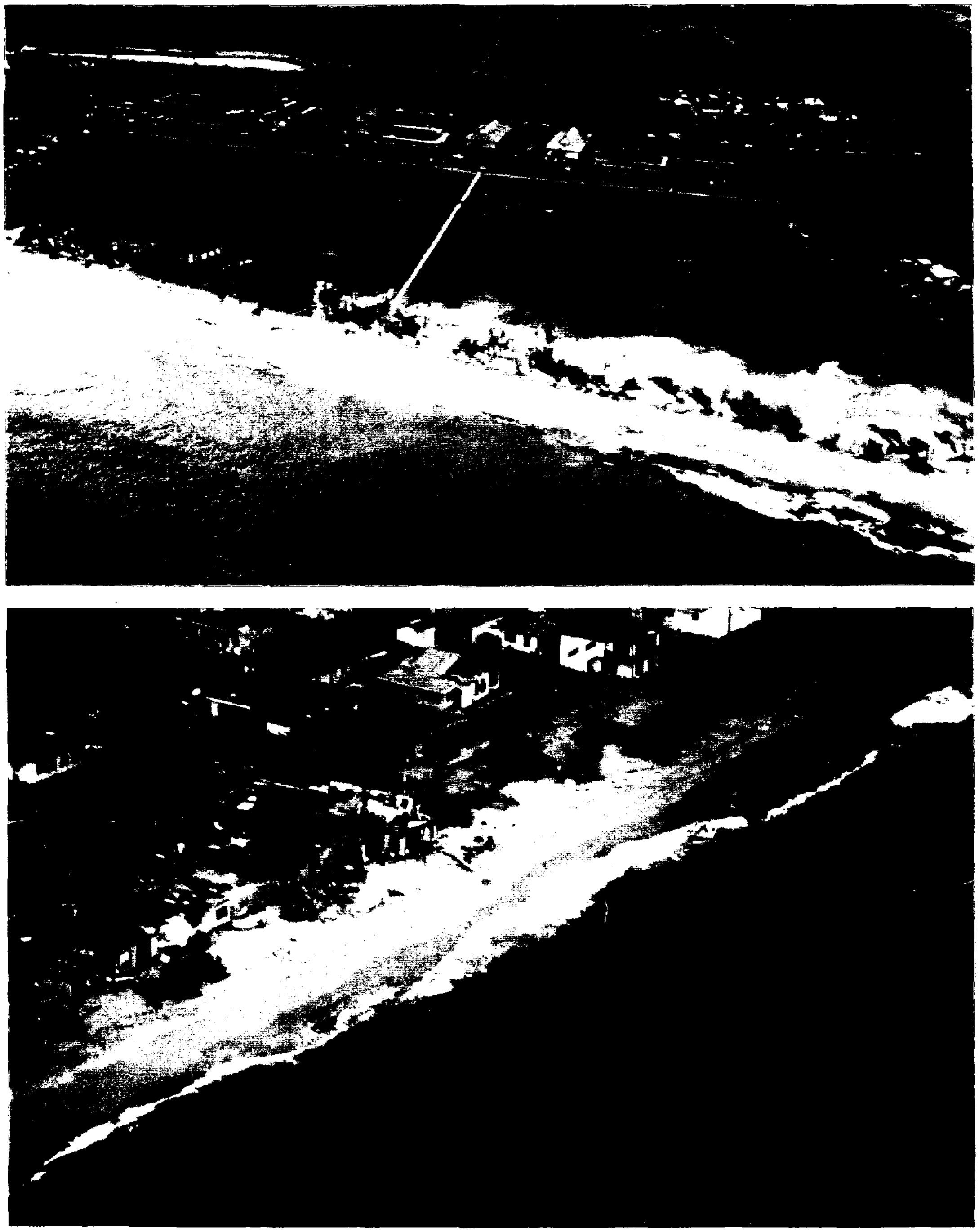


Figure 10. Top, overwash on an open field at Waipouli near Kapaa. Bottom, 200m north of the top photo, roadways and houses suffered severe damage. Overwash causes little concern where development is adequately set-back from the shore.

MAPPING THE OVERWASH

METHODOLOGY

On Tuesday, September 15, 1992 a research team composed of personnel from the University of Hawai'i, and the U.S. Geological Survey Center for Coastal Studies, conducted an aerial reconnaissance of the coastal zone of Kaua'i to assess the level of marine inundation and damage to the littoral environment. Videotapes of the entire coast were acquired to assist in later mapping exercises at an average elevation of 500 ft and a flight speed of 80 knots. Three days of ground-based surveying followed to identify the extent, and characteristics of overwash at Kekaha, Waimea, Hanapepe, Kukuiula to Kawelikoa Point, Wailua to Kapaa, Princeville, and Hanalei. Personnel from the University of Hawai'i conducted another three weeks of ground-based investigations at the same locations that autumn.

In February, 1993 a team from the University of Hawai'i conducted a series of marine surveys between Kukuiula Bay and Makahuena Point to determine the level of damage to the coral community, and the extent of debris coverage in the depth range 90 ft to the shore. The results of this study are described in a later section of this report, and in Krock and Neill (1993).

Aerial photographs at an enlarged scale of 1:1200, and high altitude NASA infra-red aerial photography provided coverage of all coastal population centers on Kaua'i. These were used in conjunction with field observations, and with survey data from the U.S. Army Corps of Engineers (Pacific Ocean Division), to construct maps of the continuous overwash line from west of Kekaha along the south and east shore of Kaua'i, to north of

Kapaa. The overwash line was drafted from field data and aerial photographic interpretation onto digital basemaps supplied by the Office of State Planning. The overwash line was digitized on the Universal Transmercator Zone 4 Coordinate System and entered into the State of Hawai'i, Office of State Planning Geographic Information System under the file heading INIKI.OWASH.

In the following sections we present and discuss maps showing the digitized Iniki overwash line, the 1986 shoreline, the FEMA Flood Hazard Zone V ("subject to inundation by the 100-year flood with the additional hazards associated with storm waves"; FEMA, 1987), and the FEMA Flood Hazard Zone A ("subject to inudation by the 100-year flood"; FEMA, 1987). These maps are State GIS products. Because of intervening shoreline movement between determination of the FIRM lines, and the overwash line, and differences in the FEMA shoreline and the State shoreline, there is some significant positioning inaccuracy in these maps. There are instances (see Waimea) where the FEMA FIRM lines wander slightly offshore. These obvious errors have been retained in the maps as an example of the inherent inaccuracies in this type of mapping technique in a dynamic environment. We estimate a positioning accuracy of $\pm$50 m.

OVERWASH CONDITIONS

A total storm-surge height of 1.8 m above mllw is recorded at near peak high tide at Port Allen, Kaua'i located 5 km southeast of eye landfall at Kaumakani. At Nawiliwili Harbor, 30 km northeast of Kaumakani, a storm-surge height of 1.7 m (mllw) is recorded. Moored wave buoys located 355 km southwest of Honolulu and 452 km south-southeast of Honolulu, recorded significant wave heights of 5.5 m and 6.0 m (10.97 m most probable maximum wave height), resp. Winds at Barking Sands Naval Facility, 22 km left of the eye, reached a maximum sustained speed of 31 m/sec (69 mph) with gusts to 45 m/sec (100 mph). At Lihue, 32 km right of the eye, sustained winds of 43.5 m/sec (97 mph) with gusts to 57.8 m/sec (129 mph) were recorded. At Makahuena Point, 20 km right of landfall, a

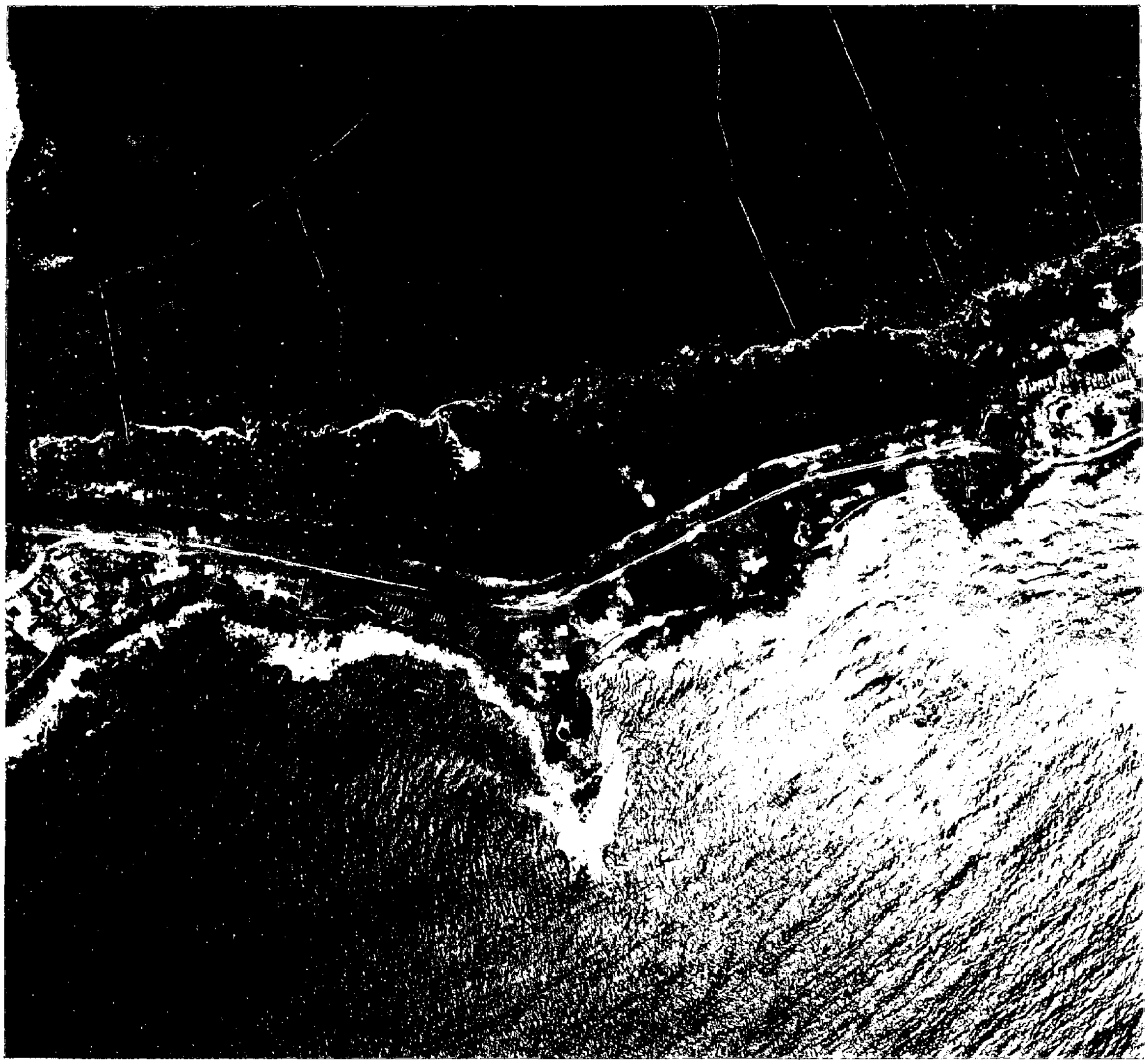


Figure 11. The overwash debris line east of Kukuiula Bay, south shore of Kaua'i. Overwash reached elevations between 4 and 5 m (mllw) along this coast. The debris line is composed of irrigation piping, housing debris, and various structural elements from the coastal developments near the water.

maximum gust value of 124 knots was extracted from the digital recorder, and we have estimated that maximum sustained winds there were between 39-42 m/sec (87-94 mph).

Overwash excursion and elevation are primarily a function of relative position and orientation to the storm core, and secondarily a function of local shoreline geometry, topography and bathymetry, and marine conditions. Maximum overwash excursions (>200 m inland) and elevations (~8.2 m msl) are not coincident, apparently this is the influence of secondary forcing parameters related to bathymetry and topography.

As we have discussed, Iniki traveled north-northeast across Kauai, exiting east of Haena on the north shore. The south coast experienced the highest overwash, and broad patterns of overwash elevation and inland excursion are relative to Kaumakani.

KEKAHA

Ten kilometers left of the eyewall, in Kekaha, maximum debris line and still-water level heights averaged 3.4 m (msl). Damage from overwash, while relatively light with respect to other areas of the island, was related to high velocity overwash flooding at the first and second line of houses in the vicinity of Oomano Point. Shore-normal streets acted as conduits for channelizing overwash, but these flows generally remained confined to the paved roads and did not cause significant damage among dwellings away from the water front. Although the revetment along Kaumualii Highway (coastal road) was overtopped by the flooding, apparently the wall was a significant factor in mitigating overwash damage to much of Kekaha west of Oomano Point. The revetment, built to halt shoreline retreat and chronic erosion resulting from the updrift (east) construction of Kikiaola Harbor, effectively reduced both the volume and velocity of the overwash in the western and central portions of Kekaha.

The history of shoreline erosion was an exacerbating factor in Kekaha, as in many other overwash areas on Kaua'i, and identifies chronic erosion as one common preconditioning agent that tends to maximize flood damage.

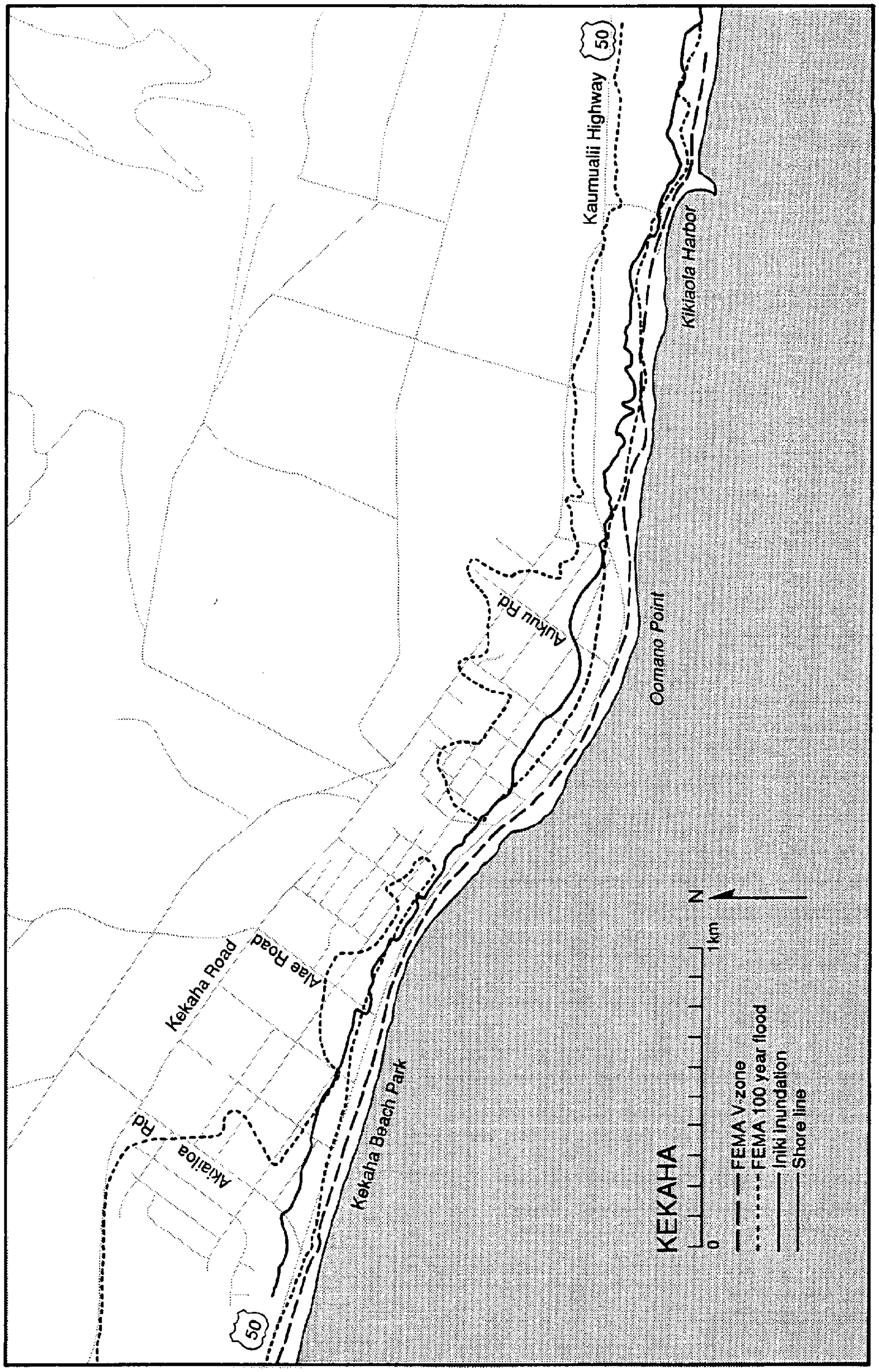


Figure 12. Overwash map of Kekaha

Abundant aeolian transport occurred in central and western Kekaha. Beach sands there are coarse-grained carbonate, whereas in east Kekaha, they are fine-grained volcaniclastics with abundant heavy minerals. Wind transport increased the amount of sand deposition occurring on the highway and immediately inland, requiring special efforts to clear roads for vehicular traffic.

Overwash excursion exceeded 200 m at Oomano Point. The overwash line takes a significant shift landward, moving from approximately one half of a city block landward of the highway to a full block and a half landward, exactly where the protection afforded by the revetment ends.

Figure 5 demonstrates that throughout the region overwash exceeded the FEMA V-Zone prediction of 100-year flooding with hazardous wave action. The overwash line falls within the 100-year flood zone, and had all buildings been elevated to the suggested AE and/or VE elevations, the level of damage would have been significantly reduced. As noted in the FEMA

Figure 13. The end of the Kekaha revetment, and the erosional offset in the shoreline caused by Kikiaola Harbor in the distance.

Figure 14. Overwash was channeled down coastal avenues, although velocity and total water volume was mitigated by the Kekaha revetment.

Building Performance Assessment Report (1992), homes that were elevated, even as little as 0.6-1 m above grade, often were spared flooding and sustained little flood damage. As also noted in that report, the level of flood damage prevented, reinforces the importance of properly elevating a structure to suggested elevations within flood-hazard areas.

The coast between Oomano Point and Kikiaola Harbor has undergone retreat at a rates of 0.15-0.6 m/yr (MOESE, 1992). Construction of the harbor in 1959 interrupted the net westward littoral drift and when erosion threatened the coast highway, the Kekaha revetment was built. Erosion continues west of the harbor, threatening the onshore stability of the west jetty which was flanked by overwash during Iniki. Flooding skirted, and partially eroded a dune system behind the west jetty and penetrated a local cemetary. Damage was minimal.

Between the harbor and the neighboring coastal town of Waimea, the shoreline is largely undeveloped and no significant structural damage was sustained other than to some lands under agricultural use, and the native vegetation. Overwash fans, extending landward 50 to 150 m, are noted in the aerial photography demonstrating that a large volume of sediment was removed from the beach and deposited beyond the active littoral zone. Much of this may be returned to the beach and littoral dunes by the tradewinds. Possible salinization of the worked soil may have occurred. The geomorphology of the backshore region is uniform, and the overwash line shows no significant features other than as reflected by variations in run-up and wave energy. Overwash elevations are approximately 1.8-2.4 m (msl).

WAIMEA

In Waimea, maximum overwash heights averaged ~2.6 m (msl). Landward excursion of the flooding was generally confined to the back beach and immediate areas (10-30 m). Marine flooding damaged the lower level of the first row of houses on the west bank of the Waimea River mouth.

The highest measured overwash in Waimea occurred near the river, ~2.5-2.8 m. Debris lines located below the top of the embankment revetment at the river mouth suggest that only minor overtopping occurred. Thus, flooding onto the low-lying coastal plain adjacent to the river was predominately marine, and did not contain any notable contribution from riverine discharge. It has been noted elsewhere that rainfall during Hurricane Iniki was generally below expected levels, and little actual river flooding occurred on Kaua'i. Precipitation at Lihue was approximately 2.3 cm, and 3 cm at Princeville (Trapp, 1993). The notable increase in marine excursion near the river was the result of the generally lower elevation around the mouth, rather than actual fluvial flooding. The east bank of the river is a high basalt exposure several meters in elevation and marine overwash was confined to a gravel beach located at the base of the headland.

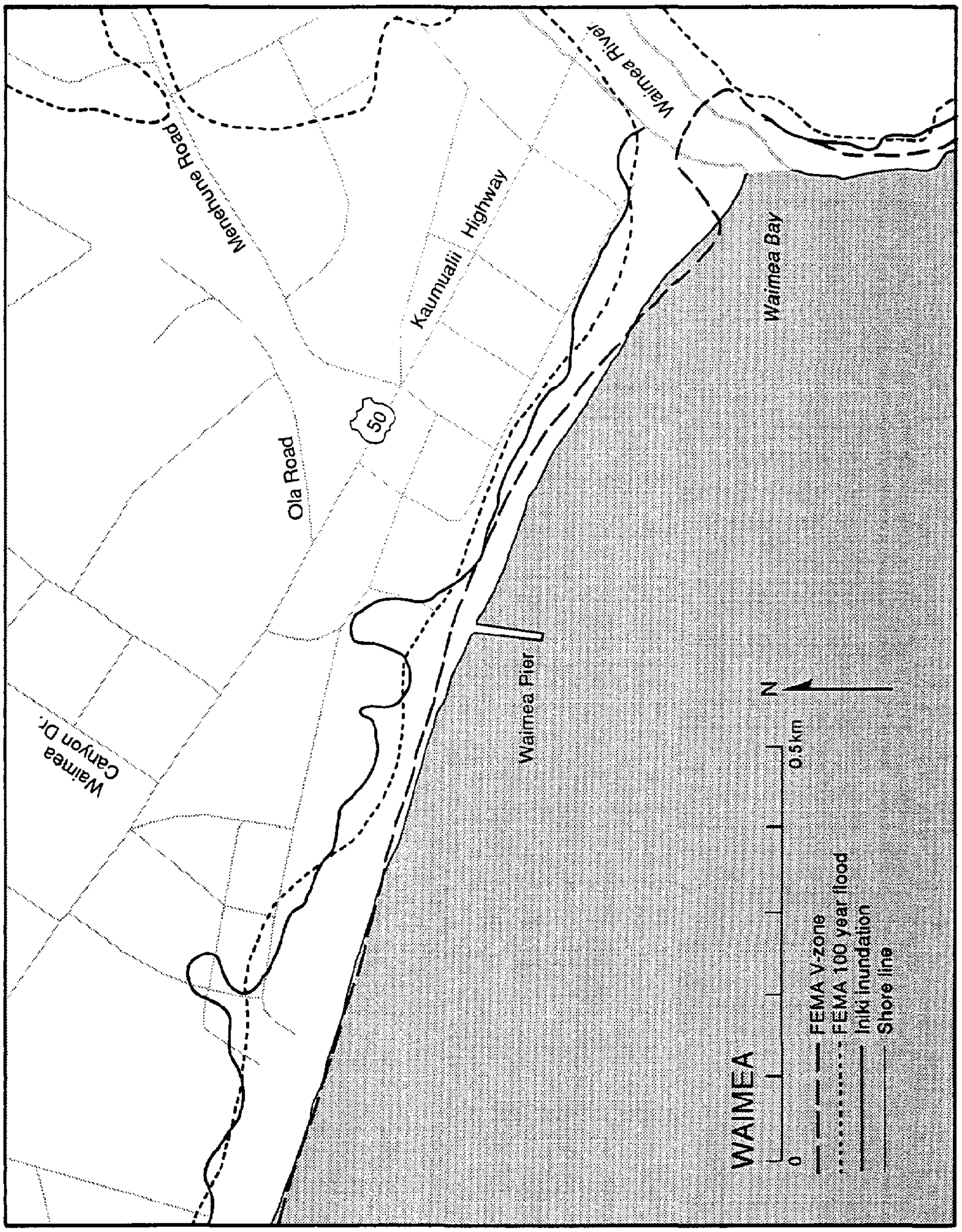


Figure 15. Overwash map of Waimea.

HANAPEPE

Hanapepe, 4.5 km right of landfall at Kaumakani, experienced maximum overwash heights exceeding 2.8 m (msl). The most extensively flooded area was on the low-lying fluvial floodplain east of the mouth of the Hanapepe River. Residents report Iniki overwash penetrated several hundred meters inland along this lowland, to the edge of the coastal highway (Rt. 50) where it crosses the river. The bridge there is a critical transportation link for

Figure 16. Overwash damage to a chain-link fence, Hanapepe Coastal Park.

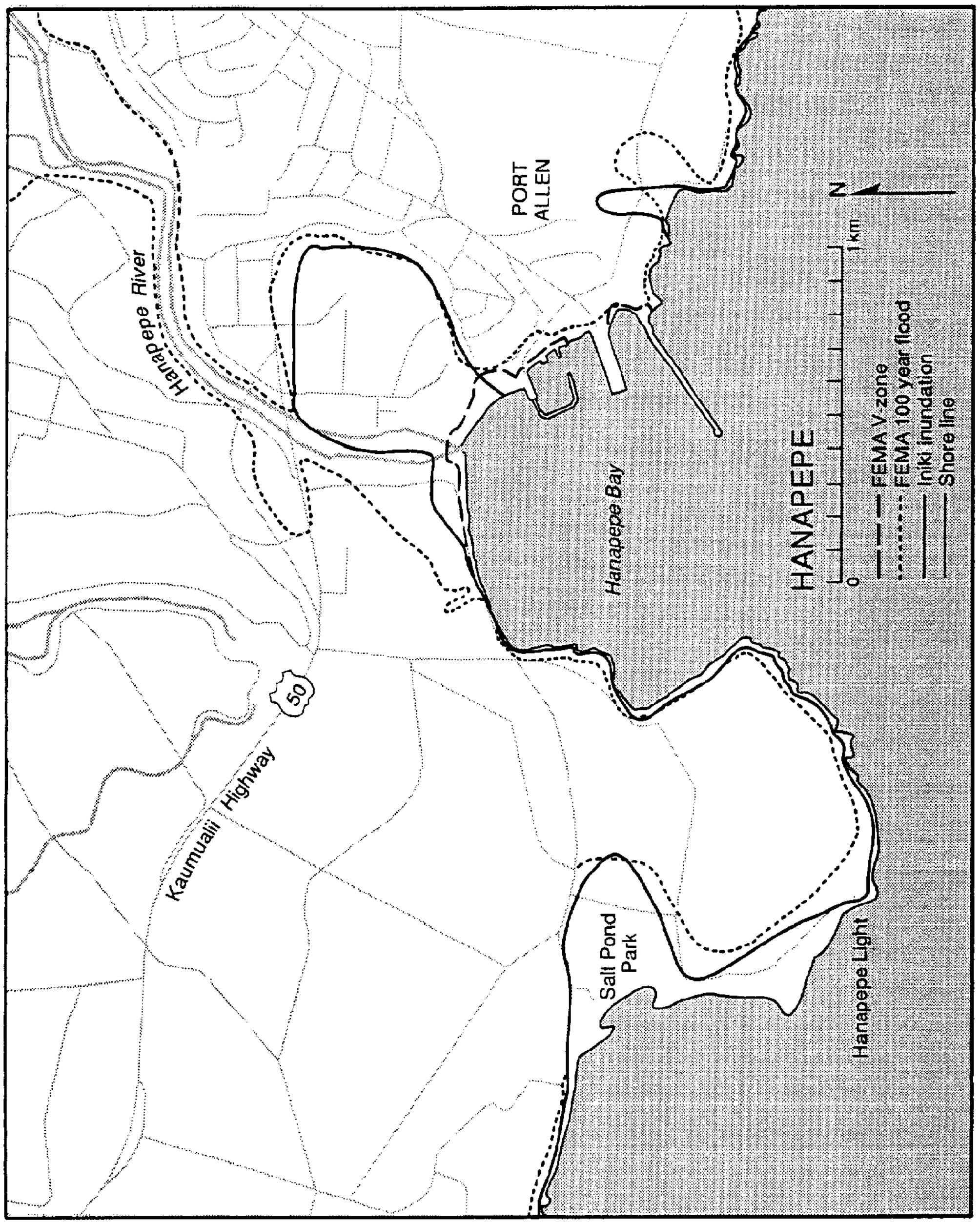


Figure 17. Overwash map of Hanapepe.

communities in west Kaua'i and a determination should be made as to whether the bridge was at any point threatened by the overwash. This region falls within the FEMA 100-yr flood Zone A, but beyond their determination for the marine hazard Zone V.

Extensive damage to the coastal park in Hanapepe Bay occurred. A revetment was one source of large boulders that were carried in suspension by the overwash and destroyed park facilities including a bathing house and tennis court fencing. Soil erosion, evidenced by scarping of terrigenous deposits behind the revetment, led to high turbidity levels in the Bay.

KUKUIULA TO KEONILOA BAY

At Kukuiula, 16-17 km right of the eye at landfall, maximum overwash around the Bay, and in the fields to the east, measured between 3.8-4.9 m (msl). Because of the low relief, the gentle onshore gradient, and the absence of offshore barriers, this sector experienced a high degree of inland penetration by marine waters. The overwash passed through a line of coastal dwellings, across a road and drainage ditch and carried debris deep into the adjacent agricultural fields. Aerial photos of the resulting debris line, in places over 250 m inland, have been widely published (Fig. 11). These provide telling testimony to the power and destructive potential of overwash in the region.

This same reach of coast was devastated by Hurricane Iwa in 1982, and was the subject of numerical modeling under contract to the U.S. Army Corps of Engineers in 1986 (Sea Engineering and Bretschneider, 1986). That work reports on scenario models that predict the overwash expected during an Iniki-type storm. One lesson learned by this experience is that numerical models of hurricane overwash have been developed to a high level of reliability, and should be incorporated in future planning along the Hawaiian coastline. Another lesson learned through the combined overwash under Iwa and Iniki, is that the coastal developments around and east of Kukuiula Bay are vulnerable to marine flooding and massive damage. Despite the obvious consequences, rebuilding activity proceeds unabated at this writing along

Figure 18. Overwash debris line near Kukuiula Bay.

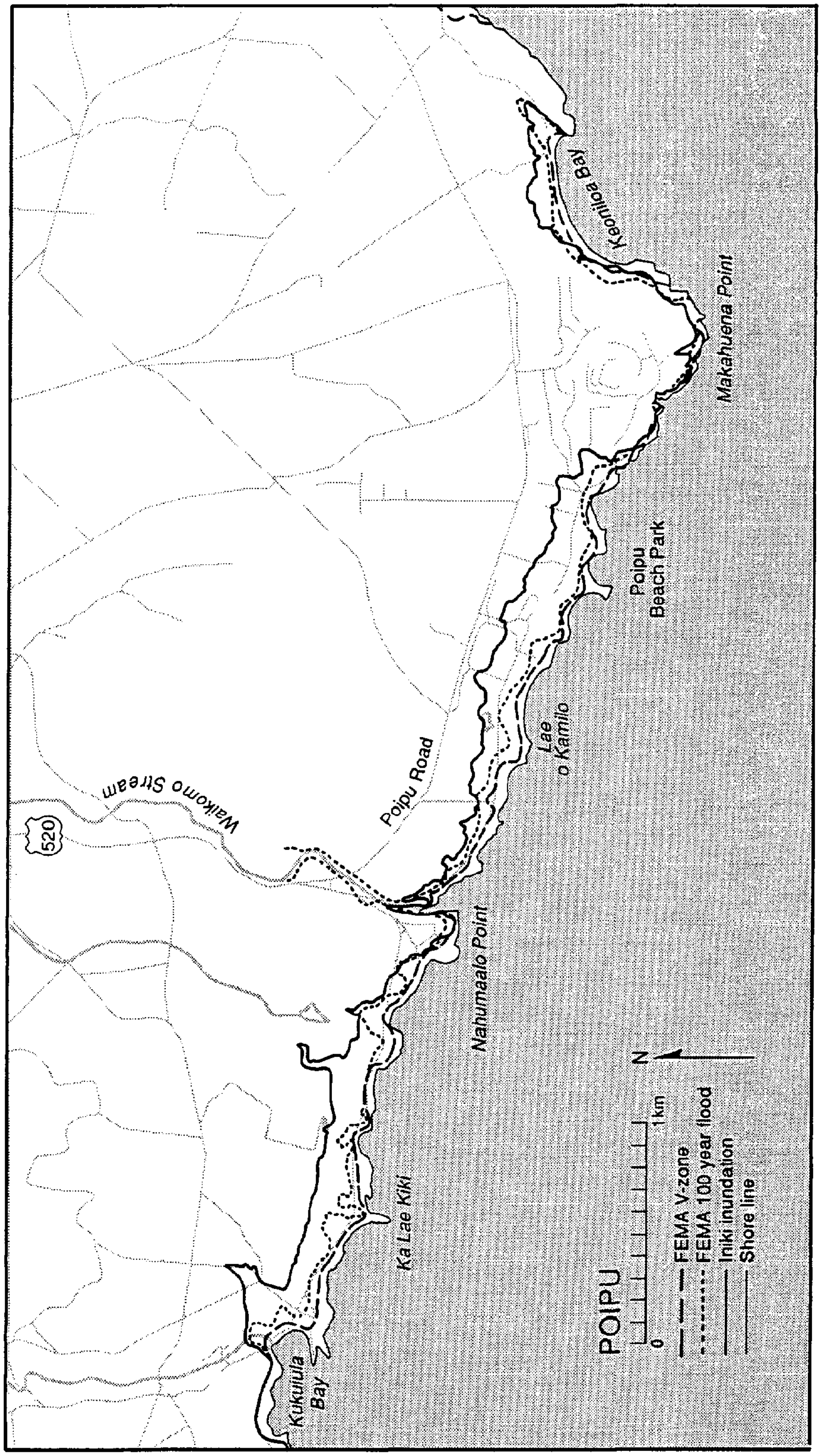


Figure 19. Overwash map between Kukuiula Bay and Keoniloa Bay.

this twice-devatated coast.

The overwash line runs well inland of coastal developments between Kukuiula Bay and Nahumaalo Point. Single family dwellings, multi-unit condominium structures, and resort hotels were all subjected to high-velocity marine flow. A double debris line in places (Fig. 18), suggests that the overwash occurred in waves and that structures were subjected to multiple episodes of flooding in a short space of time. Dry stream-beds and former natural drainage valleys contain evidence that marine penetration of inland regions was heightened by locally lower elevations. Several low-lying regions, some over 100 m from the coast, contained extensive ponded sea water and were clogged with housing and pavement debris. Local pocket beaches along this coast experienced severe erosion, and the resulting exposure of underlying soil led to high levels of coastal turbidity that persisted for over a month after the hurricane. Beach accretion has been slow to develop and at this writing, a year later, many sections of beach remain in an eroded state and have not fully recovered from the effects of Iniki. Although we cannot determine if there was pre-existing ecosytem degradation, the prolonged turbidity in the Kukuiula to Poipu coastal zone may be responsible for some shallow-water coral mortality and algal growth.

Because of the intensity and extent of overwash in this sector a number of structures sustained damage from high-velocity flooding, breaking wave forces, foundation scour and undermining, and battering by suspended debris in the water column. There are field reports of hydraulic buckeling of cement slab-type foundations, and examples of heightened damage from large boulders and paving stone literally battering down walls. At Poipu Beach Park coconut trees bear impact scars to a height of 1.8 m above ground level. Smaller structures were frequently swept off their foundations and either floated inland, or experienced destruction of the lower floors while upper floors and roofs survived to be deposited some distance inland. Residents at Nahumaalo Point report that wave spray against the headland overtopped three-story structures, and had sufficient velocity to break windows and damage roofing materials.

The highest elevation of overwash evidence, a debris line behind a small dwelling, was discovered by surveyors at the U.S. Army Corps of Engineers. This was in the area immediately east of Koloa Landing. As previously mentioned, the configuration of the coast and bathymetry there

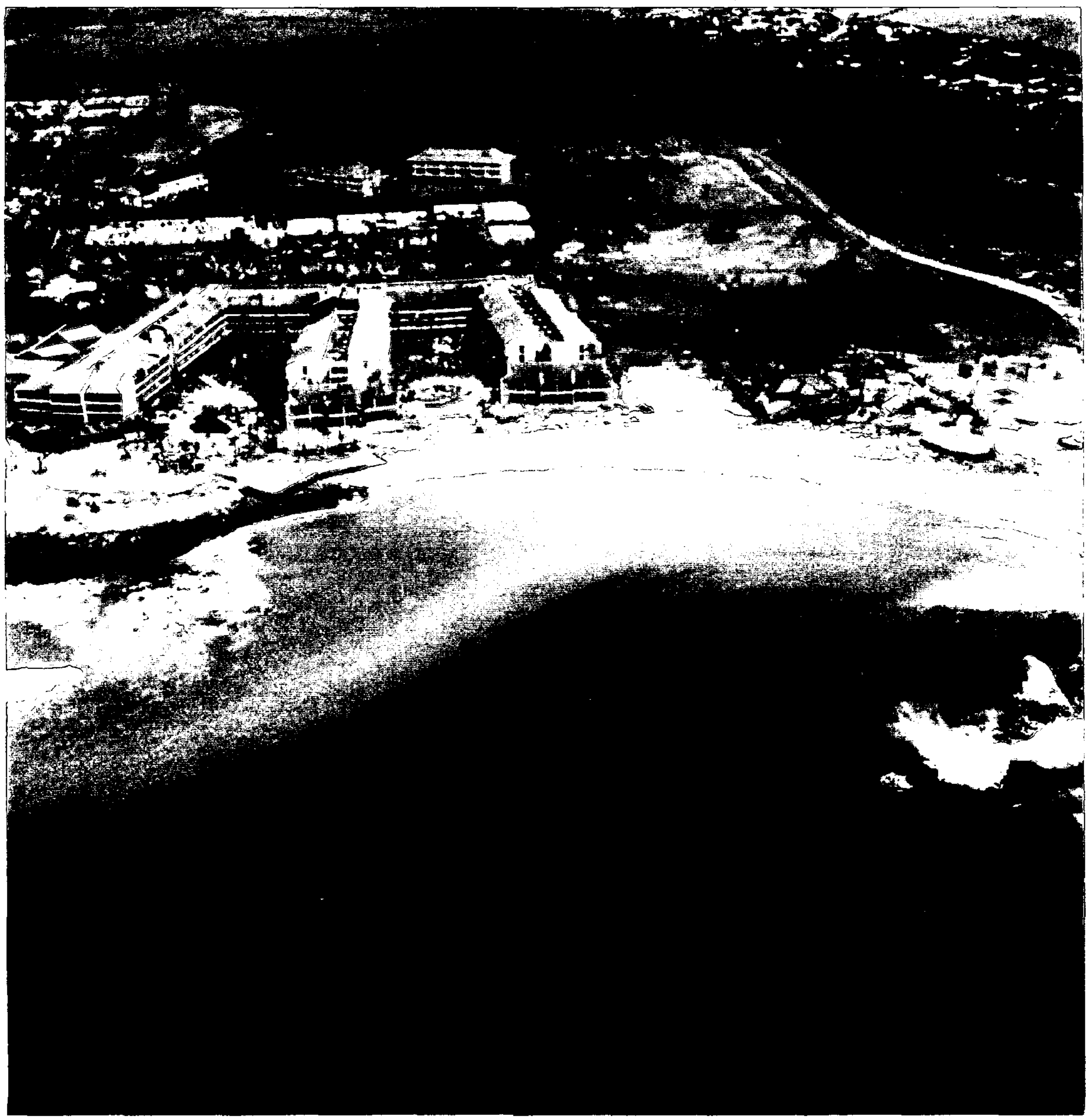


Figure 20. Coastal damage between Kukuiula Bay and Keoniloa Bay included beach erosion, coastal turbidity, structural damage from high-velocity overwash, and salinization of terrestrial environments in the coastal zone. Note overwash ponding, and the debris line behind this hotel.

apparently led to maximum run-up and breaking wave heights, and amplification of storm surge components. Debris on the road at the head of the boat ramp at Koloa measured 7 m in elevation. While to the east the maximum debris line was measured at over 8 m. Nearby, at an elevation of nearly 6 m was an overwash debris line consisting of stone blocks weighing several hundred pounds, and large household appliances.

Toward the Poipu coast the overwash line meanders inland behind townhouse and condominium developments, and the Sheraton Resort Hotel, keeping in the elevation range between 3.5 and about 5 m. Large ponds of brackish water mark upland areas where return flow collected in local basins (Fig. 20). In the parking lot behind the Waiohai Resort, automobiles were actually stacked atop one another by the overwash. The much of the subdivision landward of Poipu Beach Park and Brenecke's Beach, a popular recreation site, was overwashed. A still-water mark in a house on Pane Rd. measured 5.6 m. The small beach in front of the seawall at Brenecke's, originally destroyed by Hurricane Iwa and having only returned in recent years, was completely eroded by Iniki. One year later it has not returned.

Figure 21. Coastal damage at Poipu Beach Park.

The seawall at this locality was damaged by Iniki, and this is an excellent opportunity to remove it completely in order to encourage beach recovery and long-term stability.

On Makahuena Point, a headland with a coastal elevation exceeding 6 m (msl), the development is sufficiently set-back, and the protection afforded by the cliffs sufficiently effective, that little overwash damage occurred. That portion of the headland composed of carbonate sandstone (aeolianite) did experience some hydraulic undermining from wave action. This was also noted across Keoniloa Bay at Makawehi Point, another limestone headland. While no slumping was observed on basaltic coasts, there was overhang collapse and slumping along many sectors of limestone shore, demonstrating that a hazard is associated with development on these sites.

The beach at Keoniloa Bay was temporarily eroded, and beachrock exposed. Accretion, and the construction of a partially buried, armored overwash barrier, has since taken place. Overwash in the region of the Grand Hyatt Hotel exceeded 4 m, but damage was minimized by the wide set-back there. Unconsolidated coastal dunes in this area were cut and channelized to a depth of over 2 m where overwash apparently forced breaching of the backshore area. To the north, Mahaulepu Beach was overwashed to an elevation of 3 to 4 m, but nonetheless experienced massive lateral beach accretion exceeding 10 m because of a large sand supply available from the adjacent dune system there.

Kapaa

The highest overwash on the east coast of Kauai, in and near the town of Kapaa, was over 3 m, but averaged approximately 2.5-2.8 m. Because the Kapaa coast is oriented north-south, the winds of Iniki did not blow directly onshore for sustained periods and the additional translation speed of the storm did not exacerbate the overwash. The coastal orientation was oblique to most of the surge components. Also, waves generated by Iniki had to refract around the south coast of the island before striking the Kapaa shoreline. As a result, breaking wave heights were in the range 3-5 m. Kapaa generally did not experience extreme overwash. Nonetheless, there were pockets of extensive damage in the first row of houses on coasts with a history of chronic erosion. One of these, the Waipouli neighborhood, suffered overwash damage as a result of crowded shoreline development, low-grade housing lacking the minimum elevation suggested by FEMA flood maps, and a condition of pre-existing erosion.

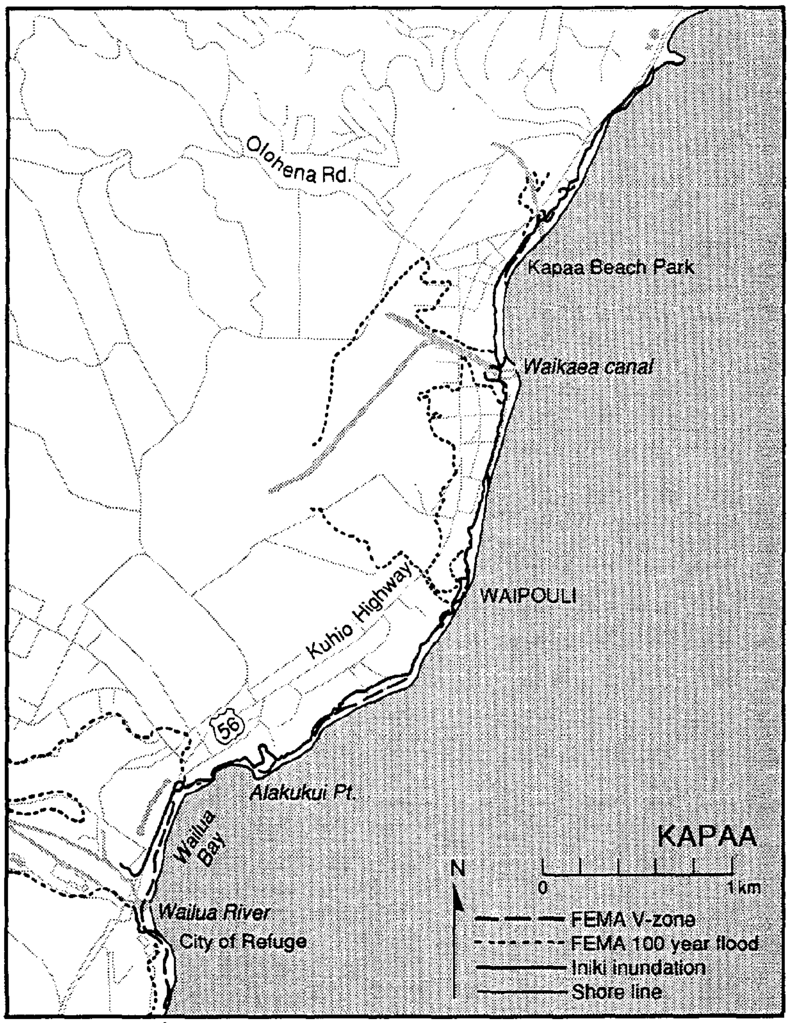


Figure 22. Overwash map of Kapaa coast.

Frontage properties in Papaloa, Waipouli, and Kapaa Town suffered damage from overwash, flooding, road washouts, and bank failure under wave assault. Coastal erosion was prevalent and beachrock exposure was a frequent tell-tale that entire beaches had been eroded. This was especially true where shorelines were armored, or soil and rock cliffs marked the landward extent of the beaches. The region between Waikaea Canal, which traps littoral sediment from the south, and Moikeha Canal, which traps littoral sediment from the north, has experienced chronic erosion for over a decade. Major portions of this coast have lost their beaches and thus had no natural buffer to absorb wave energy and dissipate run-up. Fortunately much of the development in this area is set-back behind Kapaa Beach Park, and while overwash reached significant elevations (3.4 m) and landward excursion was on the order of 25 to 50 m, structural damage was limited. South of Waikaea Canal lies yet another jettied canal at Waipouli. This, like the others, is unfortunately responsible for effectively trapping the littoral transfer of sediment. A condition of sediment starvation along nearly 2.5 km of coast is responsible for exacerbating what probably would have been a significantly less damaging overwash environment. Removal, or at the least truncation and lowering of these jetties would not only improve coastal sediment flux and lead to reduced beach erosion, possibly beach accretion, but more robust sediment storage along the coast would provide some mitigation against future overwash damage.

OTHER AREAS

HANALEI BAY: Overwash averaged 1-1.5 m and breaking wave heights were negligable because first winds (as storm approached) blew westerly and offshore, and second winds (as storm retreated) reversed to the east, while remaining offshore. Wind damage to Hanalei Town was extensive, and housing debris was noted on the seafloor at offshore sites in Hanalei Bay. No river flooding occurred, and the only coastal impact from the storm was post-event turbidity from deforested drainage areas. No observable reef damage resulted from the storm.

NA PALI COAST: Although the media initially reported that the Na Pali Coast, on the north shore of Kaua'i had "geologically aged thousands of years", in fact there was little environmental damage to the coastal zone. Our reconnaissance of this coast, by helicopter, revealed little evidence of beach erosion, no slumping of the headlands, and no evidence of alteration to the unique coastal architecture of caves and arches.

Turbidity of coastal waters was noted adjacent to streams draining uplands that had experienced deforestation and uprooting in runoff areas. But this was minor in comparison to the extensive turbidity of the Kukuiula-Poipu coast. We suspect that the relatively light rainfall associated with Iniki was an impotant reason that environmental damage was reduced in the Na Pali coastal zone. Another mitigating factor was the direction of storm movement and predominate winds that placed this sector in the lee of maximum sustained winds.

BARKING SANDS: Visits to Barking Sands recreational area and the surrounding dune fields revealed no environmental damage. Comparisons to pre-Iniki aerial photography showed no significant beach erosion, and some isolated cases of new dune formation.

PAKALA VILLAGE: Pakala Village coast was overwashed to an elevation of over 3 m and the first line of houses experienced flooding. There was also flooding in the cane field to the immediate east of town behind a small coastal bluff as evidenced by a line of dead plants. A history of erosion, and poorly engineered shoreline protection structures exacerbated the impact of the storm. No data is available regarding historical erosion rates at the site. The beach has disappeared along much of the fronting coast at Pakala, and trees are toppling into the water. Apparently erosion has been chronic and rapid.

POIPU TO NAWILIWILI Local beach erosion occured at Gilliens Beach, a local popular recreational site. As mentioned earlier, accretion was also noted in the area where beaches are backed by large dune fields. Cultural artifacts were reported exposed by the erosion at Gilliens, and strewn by the waves. Maximum overwash measured over 4.5 m in elevation. Carbonate aeolian headlands and cliffs were hydraulically excavated to the point of overhang collapse at several localities.

NAWILIWILI TO WAILUA: Nawiliwili Harbor sustained damage that was noted from aerial reconnaissance only. A large sailboat was washed broadside against the rock jetty, and several vessels sustained damage from wave surge in the harbor. Of those vessels that were hauled out, collapsed blocks apparently resulted in damage as they fell against the pavement.

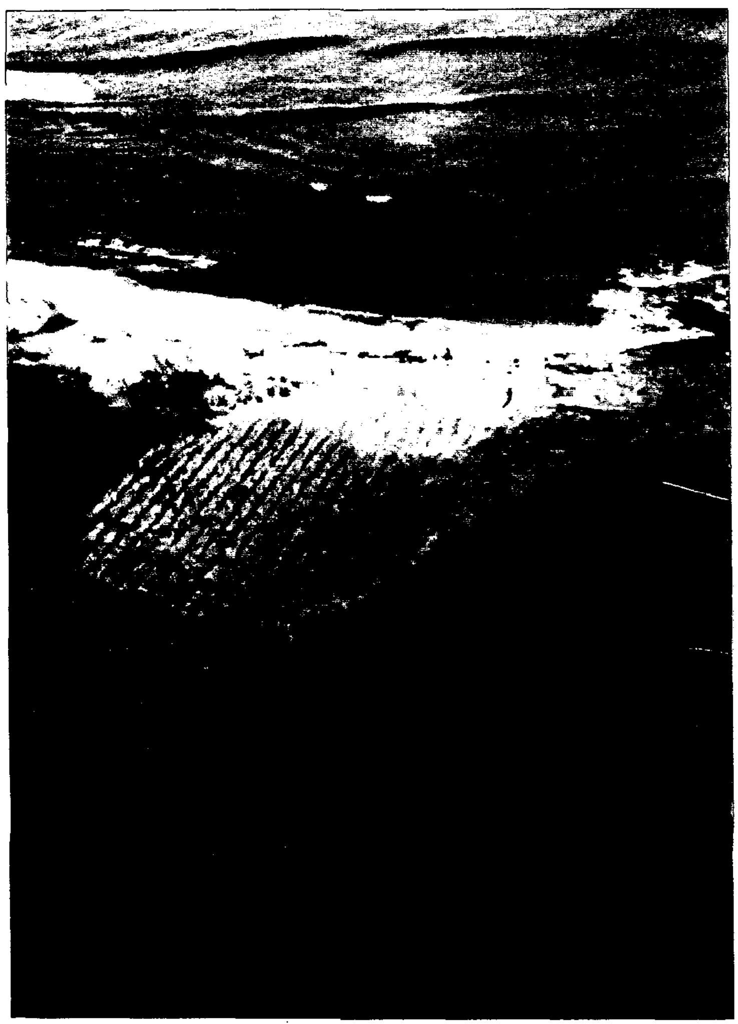


Figure 23. An overwash fan and dead sugar cane near Pakala Village.

Local beach erosion was noted along the ocean coast. Several incidents of coastal turbidity were observed, and the Wailua Golf Course revetment failed at a site that has suffered chronic erosion adjacent to a break in the fringing reef.

KAPAA TO PRINCEVILLE: The natural coastal environments along this sector apparently sustained little environmental damage. There was widespread and massive defoliation of the upland forests that led to fears of stream mouth debris build-up, a hazard that can produce flash flooding and further environmental damage. Many of the beaches in this sector are boulder ramps and suffered little under the high waves. Occasional overwash was noted from the air, to elevations of approximately 1 m or less. Rarely was the back-beach environment overwashed.

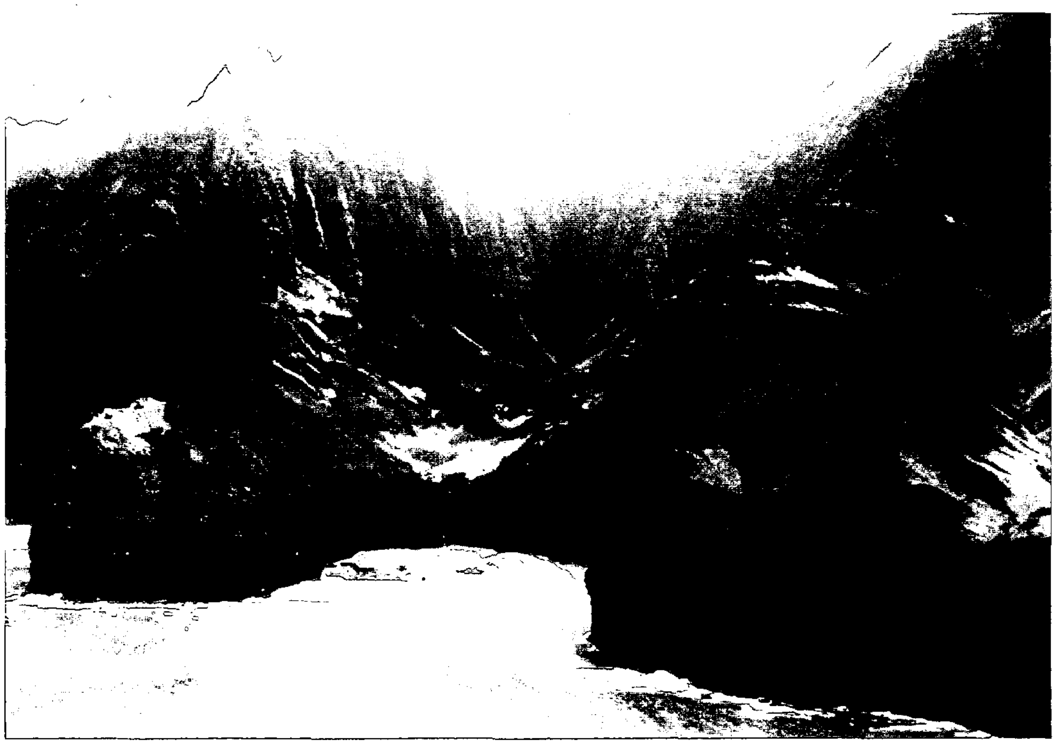


Figure 24. The Na Pali Coast suffered little coastal zone damage.

-Environmental Response-

Environmental response to the overwash varied. Beaches suffered the greatest erosion on stabilized shorelines where steep, energy-reflective faces interfered with overwash. In unstabilized regions both erosion and accretion occurred. Beach erosion exposed ferruginous soil beds that leached silt into coastal waters, and created sustained turbidity following the storm. Surveys of coral response in the region of greatest overwash (Kukuiula to Poipu) revealed slight mechanical damage to the sparse *Porites* sp. and *Pocillopora* sp. community in the nearshore region, and negligible damage in deeper offshore waters. Heightened algal growth, and coral mortality in waters shallower than 5 m may be a response to post-storm turbidity.

A short list of environmental effects in the coastal zone includes: defoliation of standing forests leading to mortality and debris build-up; soil erosion from highland regions and coastal settings; overwash mortality to coastal vegetation and agriculture; local soil and water salinization; impact damage and uprooting of trees under intense overwash; beach erosion and accretion; coastal dune channelization and erosion, some dune formation and migration; coastal soil exposure by beach erosion and leaching of soil into coastal waters causing turbidity and siltation; some coral abrasion; possible coral mortality by turbidity in the shallow zone between Kukuiula and Makahuena Point; structural debris in the nearshore zone; boulder-strewn fields across the coastal upland under intense overwash; undercutting of carbonate headlands; debris build-up by overwash.

In the remaining sections of this study, we report briefly on beach erosion, Poipu coral coverage, and offshore debris build-up.

BEACH EROSION

While many beaches sustained little erosion during Iniki, and cases of accretion were noted, the more common response of impacted beaches was to erode. We have made a qualitative assessment of beach erosion by measuring beach width on aerial photographs of the coast between Kukuiula Bay to Makahuena Point, and between the Wailua River mouth to north Kapaa Beach Park. Black and white photographs taken 7/28/87 at a scale of 1"=500', were compared to a set of color photos at the same scale taken on 9/18/92. No photogrammetric, or tidal corrections have been applied in this assessment. Our criteria for erosion were simply the recognition of minor subaerial beach narrowing (ca. <15 m change over the period 1987-1992), or significant subaerial narrowing or disappearance (ca. >15 m change over the period 1987-1992). We cannot determine when the narrowing may have occurred, but we feel there is some likelyhood that Iniki played a role on those beaches where significant narrowing was noted over the 5 year period.

Kukuiula-Makahuena Point	**Wailua River-Kapaa Beach Park**
Kukuiula Bay beach (min.)	Wailua River State Park beach (sig.)
East of Ekaha Point (sig.)	Wailua Bay beach (sig.)
Hoai Bay (min.)	Kapaa Beach Park north end (sig.)
Kaheka beach (sig.)	South of Waipouli (min.)
Kihouna Point, E&W (sig.)	Waipouli coast (sig.)
Keoniloa Bay beach, middle portion (sig.)	Waipouli Beach Park (sig.)
	North of Moikeha Canal (sig.)
Poipu Beach Park (sig.)	North of Waikea Canal (sig.)
Brennecke's beach (sig.)	South of Moikeha Canal (sig.)
Total length: 855±100 m	*Total length: 3045±100 m*

The total measured length of significantly-eroded beach between Kukuiula Bay and Makahuena Point is 855±100 m. Between the Wailua River and north Kapaa Beach Park it is 3045±100 m. These lengths include beaches that have either disappeared or significantly narrowed over the period 7/28/87 to 9/18/92.

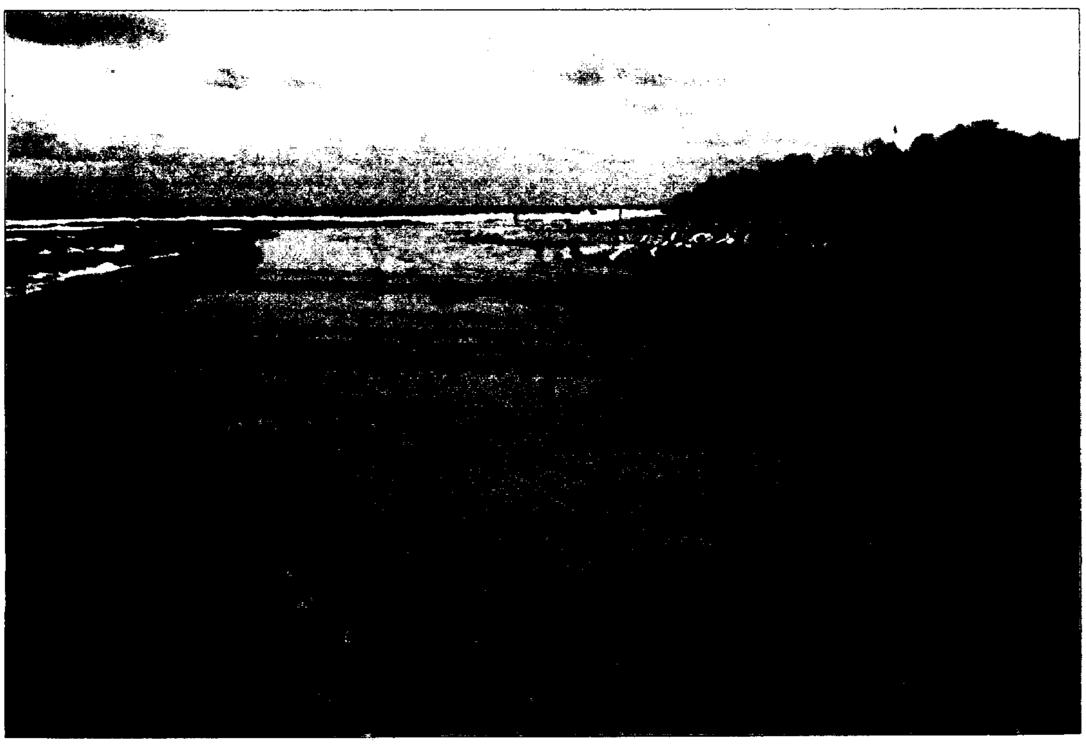


Figure 25. Top, erosion at Waipouli beach. Bottom, accretion at Mahaulepu.

POIPU OFFSHORE SURVEY

Coral Impacts - Divers surveyed coral coverage at 16 stations along the 30 ft and 70 ft depth contours in the region between Makahuena Point and Kukuiula Bay (Krock and Neill, 1993). These sites were chosen to duplicate stations used in a similar survey conducted in 1972 as part of a water quality management study for the county government (Sunn, Low, Tom & Hara, Inc., 1973). Sites were spaced approximately at 0.5 mile intervals along each contour. Sampling procedure consisted of photographing 2 to 3 representative bottom locations at each station with a reference scale and station identification number. The percentage of coral coverage in the photographs was determined by planimeter. The coral were grouped into two classes: 1.) those that present little cross-sectional profile to the nearshore hydrodynamic environment, consisting principally of the encrusting genera *Porites* and *Montipora*; 2.) and those with a larger cross-sectional profile, head coral, principally the genus *Pocillapora.*

Dr. Ralph Bowers, the biologist responsible for the 1972 survey, revisited the region following Hurricane Iwa and reported extensive damage to the coral community along both depth contours. However, his observations were not quantitative, and do not serve as a basis for numerical comparison (Krock and Neill, 1992).

Data in the following tables is from Krock and Neill (1992), and serve to illustrate several points. Over the period of observation there has been approximately a one-third reduction in total coral coverage on the 30 ft contour. This is supported by diver observations of abundant broken *Pocillapora* , and abraded and broken encrusting corals at this depth. The greatest damage was observed where unconsolidated boulder pavements are present. The 30 ft contour was the approximate depth of initial wave breaking during Iniki, and it is likely that this high-energy environment resulted in the entrainment, and saltation of many of the clasts.

The data suggests that there has been little overall change in coral coverage at the 70 ft contour. The previously dominant encrusting coral at this depth has, however been replaced by higher profile *Pocillapora*. The 1972 survey showed an encrusting coral and head coral mean coverage of about 4% and 0.5% respectively. By 1993, the relative coverage had changed to approximately 0.9% and 5% for the encrusting and head coral respectively. Although damage was noted at this depth following Hurricane Iwa (Bowers, pers. comm.), divers in the 1993 survey found very little evidence of damage despite the presence of unconsolidated boulder pavements.

If high levels of damage were sustained at 70 ft during Hurricane Iwa, it is likely that the current abundance of *Pocillapora* represents recolonization of the substrate. Although tropical storms had passed nearby, prior to Iwa, Kauai had not sustained a direct hurricane hit since Dot in 1959. The intervening 22 yr may have been enough to allow sustained coral colonization that was especially vulnerable to damage. Sport diver reports from O'ahu suggest that Hurricane Iwa caused more damage than Iniki. Possibly this is a result of the relative length of quiet periods between major storms. It is unclear if the benthic environment during Iwa was significantly more energetic than during Iniki, but there is no hydrodynamic argument to support this conclusion.

Table I.
Percent coral coverage for nearshore Kauai stations

Station	% Encrusting Coral		% Head Coral		Approx. Depth
Number	1993	(1972)	1993	(1972)	(ft)
81	1.8	(3.2)	2.7	(6.2)	30
82	sand	(1.0)	sand	(0.4)	70
83	2.5	(1.2)	4.9	(1.3)	30
84	3.0	(11.0)	3.6	(0.0)	70
85	5.0	(4.7)	3.4	(4.3)	30
86	0.2	(1.7)	0.0	(0.0)	70
87	1.2	(7.3)	4.1	(4.3)	30
88	sand	(sand)	sand	(sand)	70
89	0.7	(6.0)	10.1	(8.0)	30
90	0.1	(5.0)	6.5	(0.3)	70
91	sand	(1.5)	sand	(7.0)	30
92	0.0	(sand)	7.2	(sand)	70
93	0.3	(1.0)	0.0	(8.0)	30
94	0.1	(2.0)	7.0	(0.8)	70

Note: 1972 Data is in Parenthesis

Alternatively, the abundance of damaging clasts at the 70 ft level may have declined in the interim. Coral stress levels prior to Hurricane Iwa must also be considered in evaluating the survey results. It is possible that the benthic substrate in 1982 consisted of a large number of available clasts that accumulated over the relatively long period of quiesence since earlier storms. Increased coral damage during Iwa may have occurred as a result and the responsible materials shifted to an offshore location. There is a ledge very near the 70 ft level (at approximately 80 ft) that would serve as an effective barrier against onshore return of these clasts under fairweather waves.

Table II.
Patchiness of coral growth
Percent of area with hard substrate
Arithmetric mean and variance over mean

Station Number/ Depth	Stations w/ Hard Subst	% Encrusting Coral 1993 Mean / 1972 Mean	Var/Mean / Var/Mean	% Head Coral 1993 Mean / 1972 Mean	Var/Mean / Var/Mean
89-83	6	1.92	1.51	4.2	2.22
30 ft	(7)	(3.22)	(1.56)	(6.57)	(0.96)
82-94	5	0.86	1.61	4.86	1.56
70 ft	(5)	(3.96)	(3.67)	(0.49)	(0.35)]

Note: 1972 Data is in Parenthesis

Table III.
Estimate of gross coral coverage
Percent of area with hard substrate
Arithmetric mean and 95% confidence interval

Station Number/ Depth	Stations w/ Hard Subst	% Encrusting Coral 1993 Mean / 1972 Mean	Conf. Interv / Conf. Interv	% Head Coral 1993 Mean / 1972 Mean	Conf. Interv / Conf. Interv
89-83	6	1.92	0.14<m<3.70	4.2	1.00<m<7.40
30ft	(7)	(3.22)	(1.35<<4.58)	(6.57)	(3.94<<8.97)
82-94	5	0.86	0.00<m<2.31	4.86	1.44<m<8.28
70 ft	(5)	(3.96)	(1.06<<8.46)	(0.49)	(.001<<1.63)

Note: 1972 Data is in Parenthesis

Debris Build-up - Surveys of nearshore waters in the region revealed only limited distribution of hurricane debris. Collecting principally in channel areas, items such as lanai furniture, acoustic ceiling tiles, plastic pipes and sheeting, guttering, occasional small items from kitchens, and plastic siding were noted on an individual basis. Reports from the local sport diving community identified specific clean-up activities had been conducted on a volunteer basis following Iniki. Local divers reported having removed several large items such as bicycles, a refrigerator, micro-wave ovens, bed springs assemblies, and some household furnishings. The same individuals reported that debris was no longer a concern in this region, or in any other area they had heard of.

Field Observations - related to the diving survey are as follows:

a. There is no reef between Makahuena Point and Spouting Horn.

b. There is instead a sandy or varying volcanic bedrock seafloor consisting of: outcropping lava flows that form benches and overhangs; bouldery basalt pavements with diameters ranging from 0.5m to 2m; polygonal basalt pavements, usually in association with boulder fields, that are of low relief and smooth texture; sandy seafloor with uniformly fine to medium sand that is well-sorted and of mixed carbonate-volcanogenic mineralogy with a minor silt/organic component.

c. The sandy bottom had no coral growth.

d. The volcanic hardbottom had sporatic coral development with *Pocillapora* as the dominate genus and *Porites* sub-dominate, both genera grow in this area as separate and usually isolated patches approx. 5 cm to 30 cm in diameter.

e. Because it presents a prominate vertical profile, *Pocillapora sp.* displayed varying degrees of abrasion, breakage, and scour generally increasing in frequency in the shallow depths, and increasing where a bouldery bottom existed, several instances of total abrasion were noted where all that was left was a white scar, a former foothold, on a basalt substrate.

f. *Porites sp.* displayed a lesser degree of damage due to mechanical action.

g. Debris was absent to sparse in all sectors of the survey, there was a clear increase in the amount of debris in the shallow water zone, there were no areas of debris build-up, debris components were isolated and widespread consisting of pvc piping of varying length and diameter, aluminum gutter, kitchen storage racks, ceiling acoustic particle board, lightweight lanai funishings, some textile material, occasional plastic sheeting, and other unidentifiable components, a clean-up effort by the local population has apparently been successful in removing the majority of large and abundant debris.

h. A common debris element was fishing line wrapped around *Pocillapora sp.*, which did appear to cause damage to the coral, this would seem to be unrelated to the hurricane.

i. There was notable algal growth in the nearshore zone on every exposed surface save living coral, a significant percentage (1-5%?) of the *Porites sp.* and *Pocillapora sp.* poulation were dead and covered with algae, some (much?) of this may be due to month-long water column turbidity following the hurricane, turbidity developed because beach erosion exposed large amounts soil to wave action, silt eroded into the water for several weeks following the storm, the dramatic decrease in photic penetration may have impacted the viabilitiy of nearshore corals and resulted in the algal growth.

j. Algal growth in the nearshore (0 ft to 20 ft) was the dominate biological component of the substrate.

k. There are bathymetric highs in the coastal zone that appear to be remnant bedrock outcrops from shoreline retreat, these often have crests that are intertidal and that extend 100m or more offshore, it is likely that these bathymetric highs, and the accompanying adjacent lows (total relief of approx. 20 ft) influenced the elevation and excursion distance of the hurricane overwash by modifying the wave height at the shoreline, by increasing the immediate roughness coefficient and decreasing run-up, and by modifying the energy level and set-up.

Recomendations -

1.) No further clean-up is necessary.

2.) Continued monitoring of coral coverage and algal growth at 3-yr intervals would provide anexcellent data-set on this ecosystem in the eventuality of another storm.

3.) The algal growth should be monitored and surveyed on a 6-month interval, sources of nutrification should be identified and monitored.

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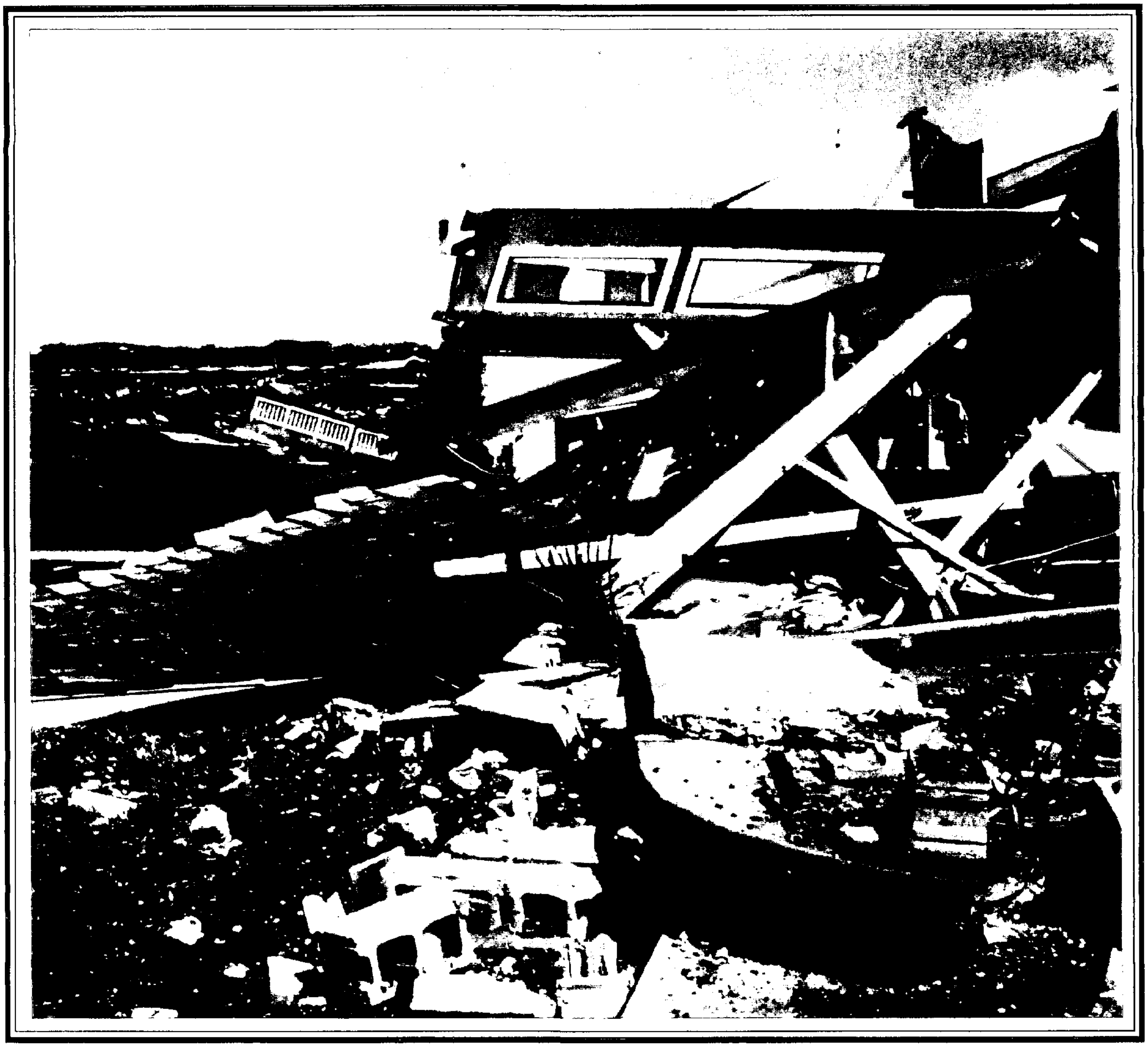

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